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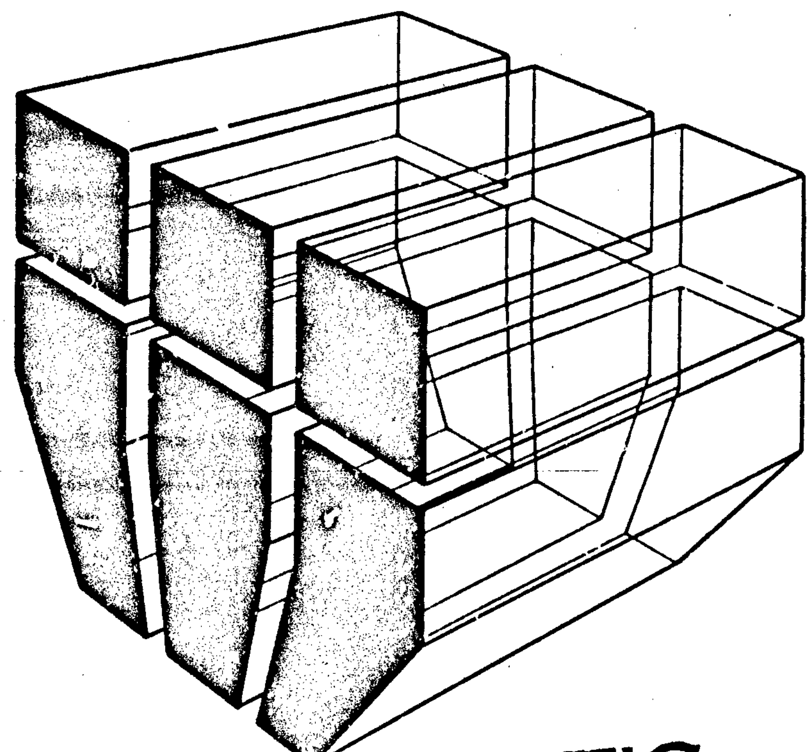
DEVELOPMENT OF CONCEPTS FOR CORROSION ASSESSMENT AND EVALUATION OF UNDERGROUND PIPELINES



by
A. Kumar
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Underground corrosion of pipelines is best controlled by taking advantage of the synergistic effects that are developed when protective coatings are used in conjunction with cathodic protection. When these techniques are not used during pipe installation, or the corrosion control system deteriorates with age, leaks and failures result. These failures require maintenance, which involves economic analysis of repair or replace options.

This report discusses the development of several new techniques for assessing and pre-

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dicting the status of underground pipe corrosion. The polarization decay principle is a nondestructive technique which can determine corrosion status without having to dig up the pipe. The Corrosion Status Index Prediction Reports show quantification and prediction of corrosion damage. Concepts for computerized and manual corrosion management systems have been developed which will enable the Facilities Engineer to determine the most cost-effective options for repairing or replacing damaged pipe.

FOREWORD

This study was conducted for the Assistant Chief of Engineers under Project 4A-162731AT41, "Military Facilities Engineering Technology"; Task C, "Operation and Maintenance Strategy"; Work Unit 041, "Corrosion Mitigation and Management System." The work was performed by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (CERL). The Technical Monitors were L. Keller and B. Wasserman, DAEN-ZCF-U.

Dr. Robert Quattrone is Chief of EM. COL Paul J. Theuer is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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DEVELOPMENT OF CONCEPTS FOR CORROSION ASSESSMENT AND EVALUATION OF UNDERGROUND PIPELINES

1 INTRODUCTION

Background

A corrosion cost study[1] has shown that the total cost of corrosion at Army and Air Force facilities is about 14 percent of the total M&R dollar. It is estimated that maintenance of underground pipelines damaged by corrosion costs $20M per year for Army facilities alone (FY83 dollars).

An Army-wide corrosion mitigation and management system (CM^2S) has been proposed which will enable the installation Facility Engineer or Director of Engineering and Housing (DEH) to determine the most cost-effective use of maintenance dollars to mitigate problems caused by corrosion.

This corrosion control program would encompass many types of structures susceptible to corrosion, including underground pipelines, underground tanks, above-ground tanks, boilers, heat exchangers, cooling towers, interior piping, metallic buildings, metallic siding, roof mount structures, electrical lines (overhead and underground), connectors, and boxes.

Controlling corrosion of underground pipelines is the first phase of the corrosion control program. Underground teel pipelines are used to collect, transport, and distribute natural gas, petroleum products, and water; containment of the product is the main concern in operating underground pipelines. Leaks and failures must be minimized to prevent property damage, ecological damage, and loss of valuable natural resources. For safety, convenience, and aesthetic reasons, most of these pipelines are located underground. The most common type of corrosion in underground (gas, petroleum products, and water) pipes is external and is caused by soil in contact with the pipe. Optimum control of underground corrosion is obtained by taking advantage of the synergistic effects that occur when protective coatings are used with cathodic protection. Some pipelines have been installed without cathodic protection or coatings, and others have coatings that have deteriorated with age, causing leaks and failures. The decision to replace or repair a section of a pipeline should be based on its present condition. Alternative repair/replace costs, application of protective measures (cathodic protection, slipline, etc.), operating pressures, and minimum safety levels must all be considered in the decision-making process.

Objective

The objectives of this study are to (1) review the state of the art of pipeline corrosion assessment, (2) develop new concepts for assessing corrosion, and (3) develop concepts for manual and computerized methods of determining the most cost-effective use of maintenance dollars to mitigate corrosion in underground pipelines.

Approach

The state of the art of corrosion assessment and management techniques was determined. A method was then developed to assess the corrosion status of undergound pipe without excavating it. Mathematical models used by the gas and petroleum industry were modified to develop a pipe corrosion status index and prediction tables. Concepts for manual and computerized corrosion management systems were developed.

Mode of Technology Transfer

It is recommended that the information in this report be issued as an Engineering Technical Note (ETN) and be incorporated into proposed revisions of Army Technical Manual 5-811-4, *Electrical Design-Corrosion Control.*

2 PIPELINE CORROSION ASSESSMENT

Current Technology

Coated steel structures that are buried in soil corrode over time. The corrosion rate depends on the soil corrosivity, coating material, alloy chemistry of the steel, and other factors. Coatings such as coal-tar epoxies, enamels, mastics, waxes, polyethylene, polyvinyl chloride, and polypropylene are seldom perfect and contain defects called "holidays." The polymeric coatings on underground steel structures degrade, and the corrosion products formed under the coating can lift and crack the coating because of the volume

[1] C. Hahin, *Corrosion Costs of Air Force and Army Facilities and Construction of a Cost Prediction Model*, Technical Report M-224/ADA042628 (U.S. Army Construction Engineering Research Laboratory, 1977).

expansion associated with corrosion. The moisture in the soil seeps under the coating and causes more corrosion, thereby increasing the exposed area of steel-to-soil corrosion action. As the structure ages, the percentage of bare steel and the corrosion products accumulated under the debonded coating increase.

Assessment of the condition of inaccessible coated pipes has long been a problem; development of life-cycle cost analyses has often been thwarted by the lack of knowledge of the pipelines' corrosion status. Buried pipes are usually inspected by digging test holes (called bell holes) over the pipe, removing the pipe coating, and visually inspecting the bare steel surface. This is an expensive process that limits the number of pipelines which can be inspected.

Corrosion of an underground structure changes its mechanical, electrical, and electrochemical properties; some of these changes can be correlated to the degree of damage. Only a few techniques used for remotely sensing a metal's corrosion status show promise for use in evaluating the condition of buried pipelines. These are discussed in the following three sections.

Mechanical Techniques

Mechanical properties, such as maximum working pressure and coating continuity, are affected by corrosion. The extent of damage due to corrosion may be determined by visually measuring the area subject to corrosion after a pipe digup. Furthermore, the reduction in area (due to uniform corrosion) or pit depths may be measured directly, yielding accurate assessments of pipe quality. Unfortunately, this technique is destructive because it requires digging up the pipe and removing a coating that might have been in good condition. Obviously, accurate, inexpensive remote nondestructive techniques for assessing a structure's corrosion must be developed.

Electrical Techniques

Electrical techniques have been developed for remote sensing the corrosion status of buried structures. These methods are based on the effect of corrosion on metal resistivity and on electrical signal transmission properties.

Manley, et al.,[2] Schmidt,[3] and Olson, et al.[4] have patented techniques to monitor metal corrosion by measuring the difference in electrical resistance, R, between a metal exposed to a corrosive medium and a similar metal standard in an inert environment. However, precise temperature control (at least control to ± 1°F between the sample and standard) or accurate temperature compensation are needed to keep deviations in R caused by thermal effects negligible. Thus, although this technique is accurate in the laboratory, its use in field applications to measure the corrosion of buried structures appears to be impractical.

Hall[5] and Bossler et al.[6] have patented techniques for locating breaks in electrical shielding of buried telephone and power transmission lines. These techniques involve exciting the cable shield with an AC signal and measuring the resulting field components in the adjacent ground with an earth prod. This technique appears to have some value in locating large pits or leaks in buried pipeline; however, its applications have not yet been investigated.

Erath[7] has patented a technique for measuring the quality of insulation of a buried pipeline and the amount of metal oxide present at breaks in the insulation. The test is conducted by impressing and alternating voltage between a buried pipeline and a ground bed. The location of breaks or openings in the coating is determined by surveying the current distribution around the pipe. This allows identification of the sources of high currents, which are breaks in the coating.

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[2] R. E. Manley, et al., U.S. Patent 4,019,133, "Corrosion Detecting and Monitoring Apparatus" (April 1977).

[3] T. R. Schmidt, U.S. Patent 4,217,544, "Method and Apparatus for Improved Temperature Compensation in a Corrosion Measurement System" (August 1980).

[4] E. E. Olson, U.S. Patent 4,262,247, "Making and Using Corrosion Measuring Probes for Fluid Conveying Conduits" (April 1981).

[5] T.L. Hall, U.S. Patent 2,860,304, "Detector" (November 1958).

[6] F. C. Bossler, U.S. Patent 3,792,350, "Detection of Metal Shield Faults in Buried Cable" (February 1974).

[7] L. W. Erath, U.S. Patent 4,099,117, "Method and Apparatus for Measuring the Quality of Insulation on the Buried Pipeline and the Quantity of Metal Oxide Present at Breaks in the Insulation" (July 1978).

The presence of oxides is verified by measuring the strength of harmonics of the input AC signal. This is based on the fact that the transmission of an AC signal through some metal oxides produces unique harmonic frequencies; for example, iron oxide and copper oxide produce 3f and 2f harmonics, respectively. Erath noted that the quantity of oxide may be determined by comparing the strength of the harmonic signal of interest to the strength of the current flow. He defined a parameter called the electrical quality of the pipe to describe the overall pipe quality. This parameter is found by taking the ratio of the reactive component of the current to the resistive component of the current as produced by a voltage source of frequency, f. This technique shows promise for the remote sensing of the extent of corrosion of underground pipelines, although it seems that a highly skilled operator is necessary for data collection.

Electrochemical Techniques

Several electrochemical techniques for analyzing metals corrosion are available; many of these are summarized in the NACE publication "Electrochemical Techniques for Corrosion."[8] However, the translation of these techniques from laboratory to field applications is often not practical or possible. The electrochemical techniques which now appear feasible include determination of the current required for a 20-mV to 15-mV shift in potential. The criteria currently used for cathodic protection require that a protection current of 2 mA/sq ft of bare area be supplied through the structure and that the "instant off" potential of the structure be −0.75 V vs. a Cu/$CuSO_4$ reference cell for steel structures. The bare area of the structure can be determined by noting what current is needed to obtain a desired shift in polarization potential, assuming that the total surface area of the structure and all adjacent structures that are electrically continuous are known or held constant during the life of the structure.

The "size" of a buried pipeline does not stay constant over its life due to factors such as pipeline expansions, improper installation of new underground structures (which results in electrical contact among different systems), or corrosion of threaded pipe joints (which causes electrical discontinuity between sections because of high contact resistances). However, the amount of pipeline that is electrically continuous may be established by conducting a potential survey during polarization. This technique allows relatively accurate assessment of the quality of buried structures under controlled conditions. However, it is often tedious and requires highly qualified personnel for measuring data and evaluating subsequent results.

Status Summary

Techniques for evaluating the status of buried structures are far from optimization. New techniques or optimization of existing techniques are needed to provide measurements that are nondestructive, accurate, economical, and nonpersonnel-intensive.

Development of the Polarization Decay Technique

CERL has recently developed the polarization decay technique, which, when refined, will provide an accurate, economical means of measuring the corrosion status of underground pipes in soil. The technique has been tested in the laboratory and has provided acceptable measurements. Figure 1 shows the pipe corrosion monitor and associated apparatus used for this technique. The underground pipe is polarized by passing current through a temporary ground rod. The electric current flows from the temporary ground rod to the pipe through the soil. An electrical connection to the pipe is made either at the pipe riser, where the pipe comes out of the ground and goes into the service structure, or by using a probe bar. A current interrupter is used to shut off the current from a DC power source 60 times per second. A volt meter which is tuned with the current is momentarily shut off by the interrupter. Therefore, only the "instant off" current potential is measured. Interference from the potential IR drop caused by the current flowing through the soil of relatively high resistance is therefore avoided. The IR drop arises because the reference cell, such as Cu/$CuSO_4$, is placed on the ground about 3 to 6 ft above the pipe. The current flowing from the temporary ground rod to the soil and into the corroded areas of the underground pipe interferes with the noncontacting reference cell placed on the ground. The rest potential of the pipe is shifted by −150 mV. The current is passed for 1/2 hour while maintaining the off-potential shift at −850 mV with respect to the Cu/$CuSO_4$ reference cell. Then the current is shut off and the polarized pipe is allowed to decay by V, usually 100 mV in time, t seconds; the relaxation rate, R, defined by $V/\Delta t$ per unit area, is then determined. A chart recorder is used to measure the rate of relaxation of the pipe's induced potential.

[8] R. Babobian, "Electrochemical Techniques for Corrosion" (National Association of Corrosion Engineers, Paper presented and published in 1977).

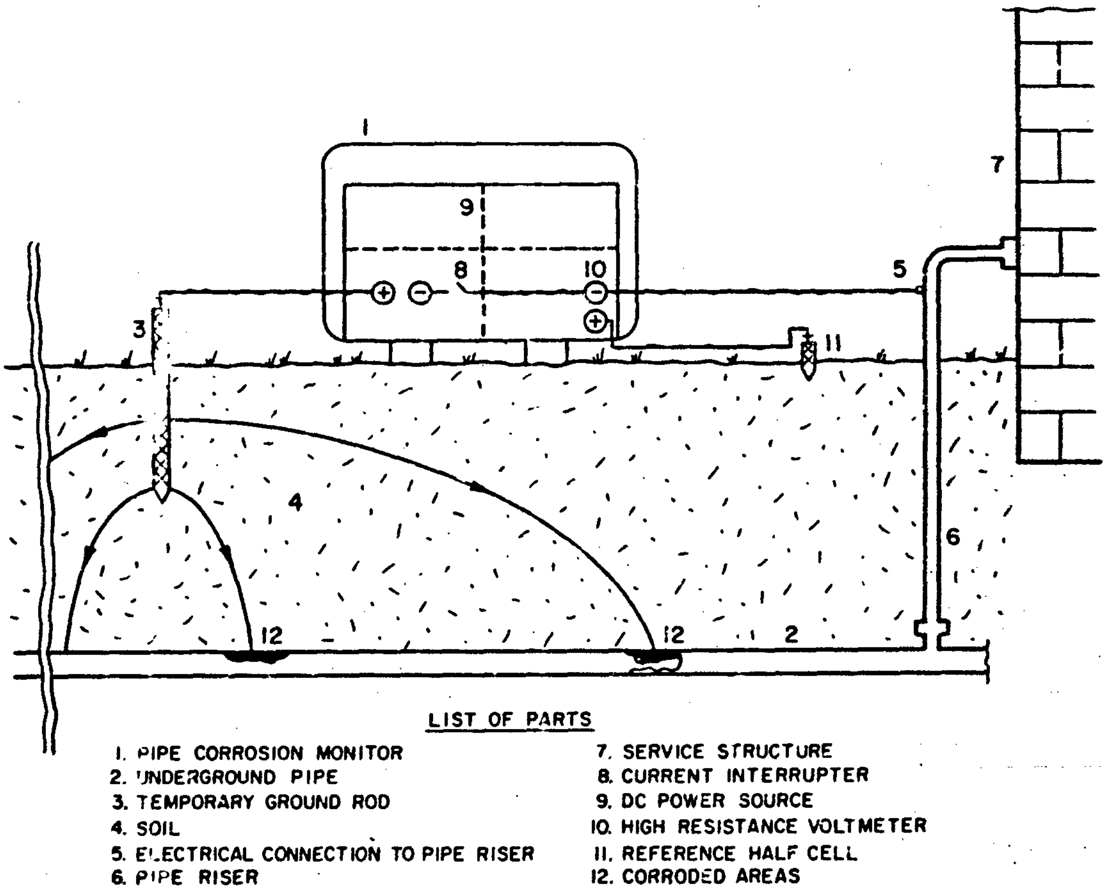

Figure 1. Pipe corrosion monitor schematic.

Figure 2 shows a typical polarization decay plot in tap water for a pipe having 0.1 percent bare area. In the region A-B of Figure 2, the "instant off" potential is controlled at −150 mV shift from the natural rest potential. At B, the controller is shut off and the potential of the pipe is allowed to decay naturally.

R has been correlated with the corroded area fraction, F, as determined by controlled calibration tests in tap water. Laboratory tests of coated pipes in tap water of 4000 ohm.cm resistivity have shown that R is approximated by:

$$R = A \times F^{0.4} \qquad \text{[Eq 1]}$$

where A is a constant.

Another function, called the Cathodic Protection Index (CPI), has been developed for use in corrosion testing.[9] It is defined as:

$$CPI = \frac{\Delta V}{\Delta I} \qquad \text{[Eq 2]}$$

where ΔV is the shift in the volts required to shift the pipe potential by −150 mV and ΔI is the current requirement for the potential shift.

[9] A. Kumar and D. Wittmer, "Coatings and Cathodic Protection of Pilings in Seawater: Results of 5-Year Exposure," *Materials Performance*, Vol 18, No. 12 (1979), pp 9-14.

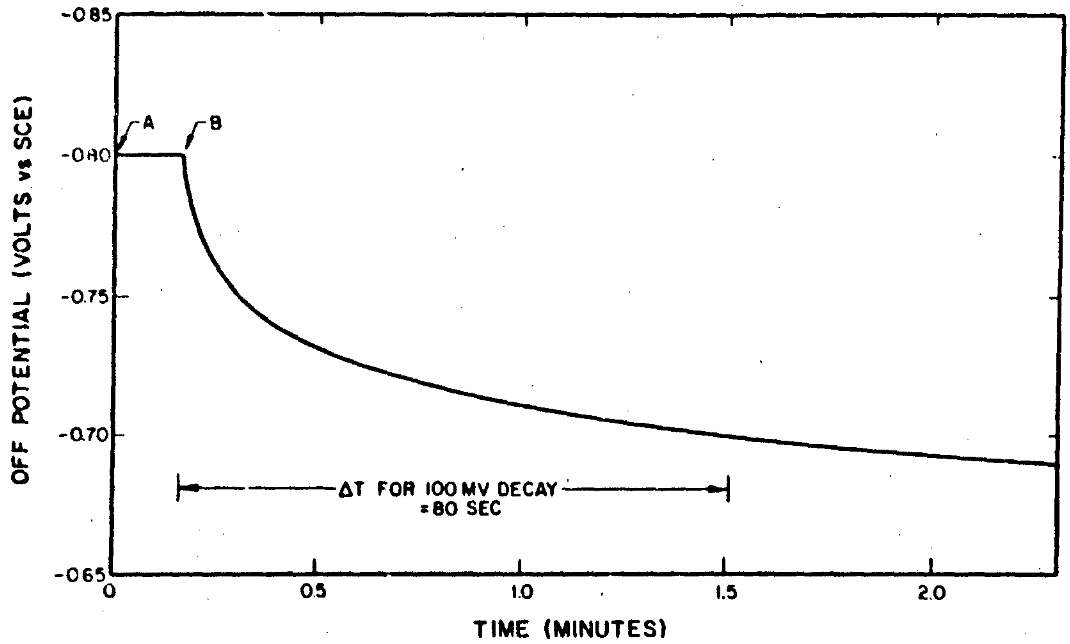

Figure 2. Typical relaxation rate curves.

The CPI has been approximately correlated with the fraction of F in controlled calibration tests by:

$$CPI = B \times F \qquad \text{[Eq 3]}$$

where B is a constant.

Figure 3 shows the relaxation rate (time for 100 mV decay) of induced polarization as a function of the percent of bare area of steel pipe.

In actual field conditions, the length of the underground pipe polarized by the temporary ground bed will depend on the electrical discontinuities in the pipe. Sections of the underground pipe which are connected electrically can be polarized with a single temporary ground rod; again, only the sections in contact with soil are polarized. The area of the pipe to be polarized can be determined by making surface potential measurements by placing a reference cell on the ground on top of the pipe; the other lead of the potential measuring device is connected to the pipe riser. Eq 1 can be used when sections of underground pipe are electronically discontinuous or have threaded joints which have been corroded. Eq 3 could be used when a large area is electrically connected and there is no interference from other foreign pipes in the ground.

3 EVALUATING AND PREDICTING PIPE CORROSION STATUS

Corrosion Status Index

In any decision-making process, the corrosion status of the underground pipe must be quantified. CERL has developed a corrosion status index (CSI) to characterize the condition of underground pipe. The pipe is given a numerical rating from 1 to 100, where 100 represents a newly coated pipe and 1 represents a completely deteriorated pipe. The CSI can be calculated by obtaining information on soil corrosivity (resistivity, pH, etc.). Future CSI may also be predicted, which will allow various maintenance strategies to be compared. The pipe corrosion status index (CSI) is defined as:

$$CSI = 100 - 100 (Pav/T)$$

where Pav is the average pit depth of a 1-m section of pipe and T is the thickness of the pipe wall. It has been empirically observed that Pav/Pmax = 0.7, where Pmax is the depth of the deepest pit. The first leak starts when Pav = 0.7T or, by definition, when CSI = 30.

CSI can be estimated by one or, preferably, a combination of the following techniques: (1) dig-ups

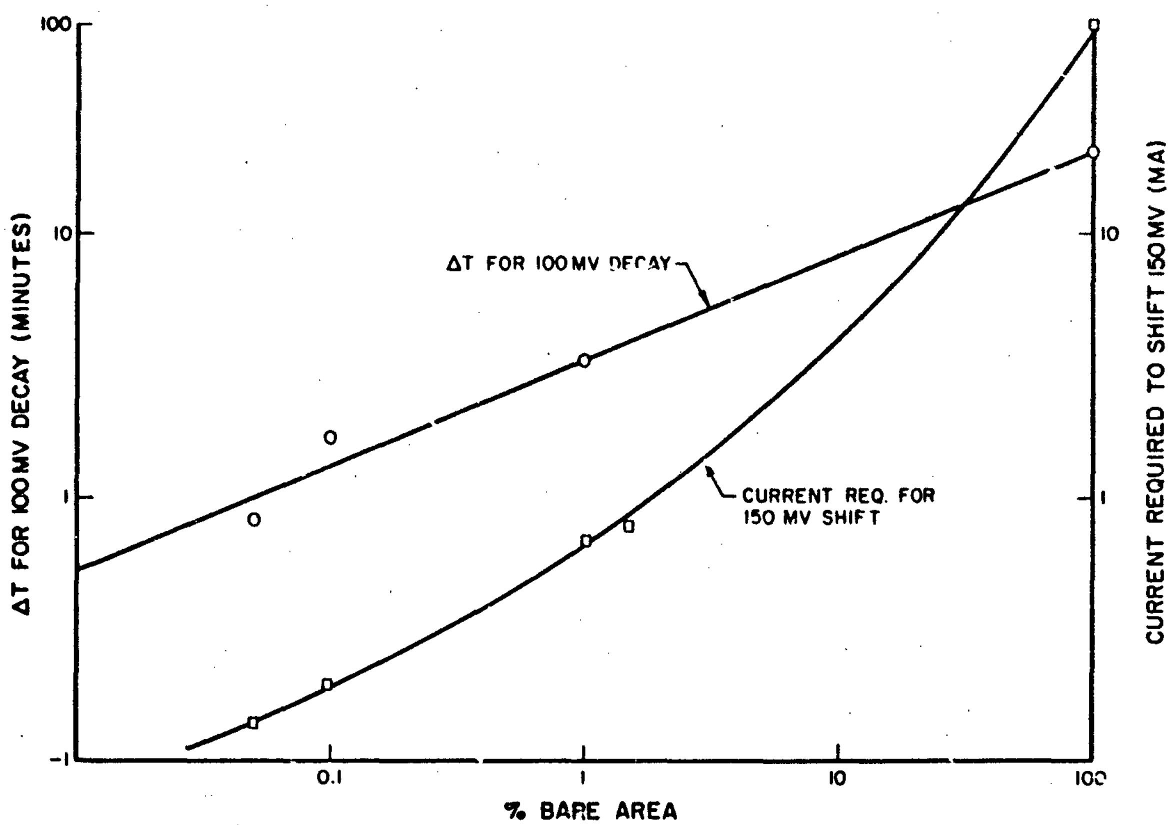

Figure 3. Relaxation rate for 100 mV decay as a function of bare area for pipe in water-laboratory tests.

and pit depth measurements, (2) electrical polarization techniques, and (3) predictions based on a mathematical model. Dig-ups and pit depth measurements are the most common method used but are also the most costly—$1000 for each dig-up and inspection (1983 dollars).

Sampling for dig-ups consists of inspecting pipe conditions (measuring pit depths) at predetermined intervals on a pipeline section. The sample areas are chosen based on soil properties and age of the pipes. Two things are important in sampling: (1) spacing of inspections, and (2) size of area inspected. One statistical study on a 25-mile length of oil pipeline by Romanoff[10] has shown that the true average pit depth remained with the average values, regardless of the number of inspection points. He inspected at intervals of 1/8, 1/4, 1/2, and 1 mile. For the pipelines being considered, 25 inspections at 1 mile apart gave an approximation of line conditions that was as good as one provided by 6384 inspections at 20 ft apart. Thus, one inspection per mile of pipeline is enough to determine the average pit depth. In determining how much pipe should be exposed at each inspection point, it has been observed that the average maximum pit depth obtained by a large number of inspections, each of an area 1 ft long, is almost as representative as the numbers obtained when the entire joint was exposed. A comparison of the maximum pit depths for different starting points on 5-mile-long lines of equally spaced inspections showed that the average was independent of the starting point. Therefore, it is concluded that for each different soil and each different pipe length, adequate sampling should consist of 1-ft exposure sections at an interval spacing which will maintain the desired degree of accuracy.

The maintenance models are less expensive for use, but provide less accurate estimates. Electrical polarization techniques (see p 9) have been developed, but have not yet been field-tested.

[10] M. Romanoff, *National Bureau of Standards Circular 579* (1957), p 168.

Prediction of Pipeline Corrosion Status

Prediction of corrosion status or damage caused by soil corrosion has been a subject of intensive study since before 1920. The relevant parameter which causes pipe failure is maximum pit depth or penetration. The uniformity of corrosion is of less interest than the maximum pit depth because pipes act as containers. The failure of the pipe can be caused by one pit penetrating through the wall thickness of an underground line. Therefore, for prediction purposes, the selective attack by soil to cause pits distributed over a length of pipeline is of concern.

The corrosivity of a soil is a complex function of many variables and has not yet been established statistically. Soil composition parameters such as moisture, sulfides, pH, conducting ions such as chlorides, etc., must be measured and averaged over the length of pipe in contact with the soil. The composition of the soil in contact with the pipe must also be measured. The very act of excavation and pipelaying disturbs the soil; the backfill surrounding the pipe becomes mixed and aerated, giving the characteristics different from those of the undisturbed soil near the pipe.

The rate of pit growth is generally 10 times faster than uniform corrosion and is therefore more important. In 1922, the National Bureau of Standards began a program to determine the relationship between soil characteristics and corrosion of buried metals. The data has been summarized in a comprehensive document.[11] This work was very intensive, extending over 30 years, and the data were compiled on 37,000 specimens. In another study, the petroleum industry developed a statistical model that would predict underground gasoline tank leaks from 10,000 sites throughout the United States and Canada.[12]

Once leaks from pitting caused by soil corrosion occur on an unprotected pipeline (or on a partially protected pipeline), they will continue to occur at an increasing rate. The future frequency can be predicted with reasonable accuracy after a few leaks have occurred on a line or section (see Figure 4).

To estimate the number of leaks caused by external corrosion, one must estimate both "age to leak" and "accumulated leaks" over time. As is common with deterioration mechanisms, the plot of cumulative leaks against time is an exponential function. The reliability of predicting the cumulative leaks is better than that of "age to leak" prediction.

A field experiment designed to statistically model and predict corrosion damage and leaks on gas lines would be very expensive and would have to last 50 years. Large sections of pipes would have to be buried in soils having different characteristics; then pit depths and the soil environment would have to be monitored accurately and measurements taken by qualified corrosion scientists and a statistician. In the absence of such a study, a model has been developed which incorporates features from previous studies. It is presented in the form of curves and tables (see the appendix) because it is too complex to be expressed mathematically in a set of simple equations.

As more data are collected and results become available, the parameters will be re-estimated and the model updated. Generally, the best data will be generated whenever data collection is supervised by someone technically qualified in corrosion research and familiar with both the corrosion mechanism and statistical procedures.

The features listed below have been incorporated into the preliminary computerized "look-up" tables to estimate the CSI:

1. The effect of coatings/bare metal in soil corrosion (New York State Culvert Study[13])

2. The effect of pH and resistivity on years to perforation (California State Culvert Study[14])

3. Average number of years to leak (East Ohio Gas Data[15])

4. Prediction of maximum pit depth from average pit depth (East Ohio Gas Data[16])

5. Rate of pit growth with time (East Ohio Gas Data[17] and Putnam[18])

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[11] M. Romanoff, p 168.

[12] Warren Rogers Associates, Report by Special Task Force on Underground Storage Tanks, Appendix E (Petroleum Council for the Protection of Canadian Environment, 1980).

[13] *Culvert Corrosion Investigation* (New York State, 1960).

[14] J. L. Beaton and R. F. Stratfull, *Proceedings of the Annual Meetings*, Vol 41 (National Research Council Highway Research Board, 1962).

[15] *Procedures for Evaluating Pipeline Replacement* (East Ohio Gas Company, 1979).

[16] *Procedures for Evaluating Pipeline Replacement.*

[17] *Procedures for Evaluating Pipeline Replacement.*

[18] J. I. Putnam, "Soil Corrosion" *Proceedings*, 16 IV 66 (American Petroleum Institute, 1946).

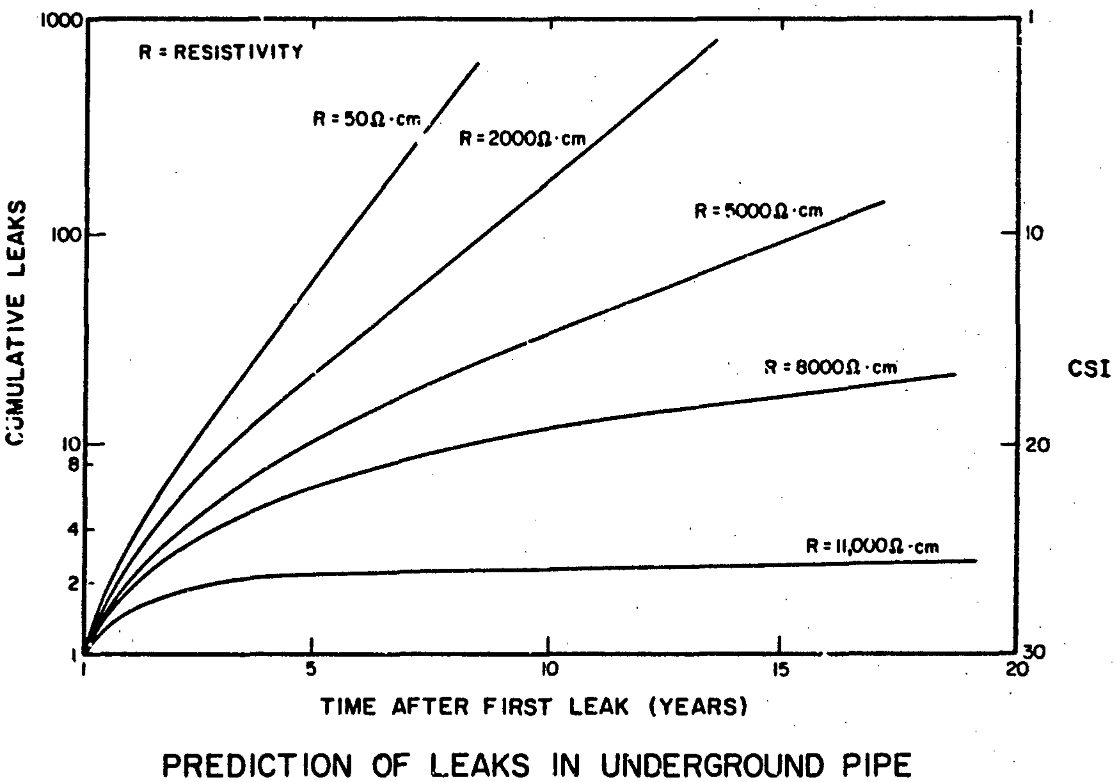


Figure 4. Prediction of leaks in underground pipe.

6. Effect of sulfides

7. Effect of moisture.

Based on the "look-up" table, typical curves showing the effect of wall thickness, pipe coating, and resistivity are shown in Figures 5, 6, and 7, respectively. The appendix provides typical detailed computer plots for CSI prediction.

The preliminary prediction table was created from literature dealing with the consequences of corrosion. The average number of "years to leak" was obtained from East Ohio Gas data[19] for coated nominal 2-in. gas lines in Ohio soil. This soil had an average resistivity of 9000 ohm.cm and a pH of 7, and its average number of "years to leak" was 29. The average wall thickness of the gas lines was 0.2360 in. The functional variations of soil resistivity and pH observed by Beaton and Stratfull on culverts (see Figure 8) was assumed to be true for gas pipes. It has been established[20] that soil properties such as resistivity, pH, etc., should be

[19] *Procedures for Evaluating Pipeline Replacement.*

[20] J. L. Beaton and R. F. Stratfull; Warren Rogers Associates.

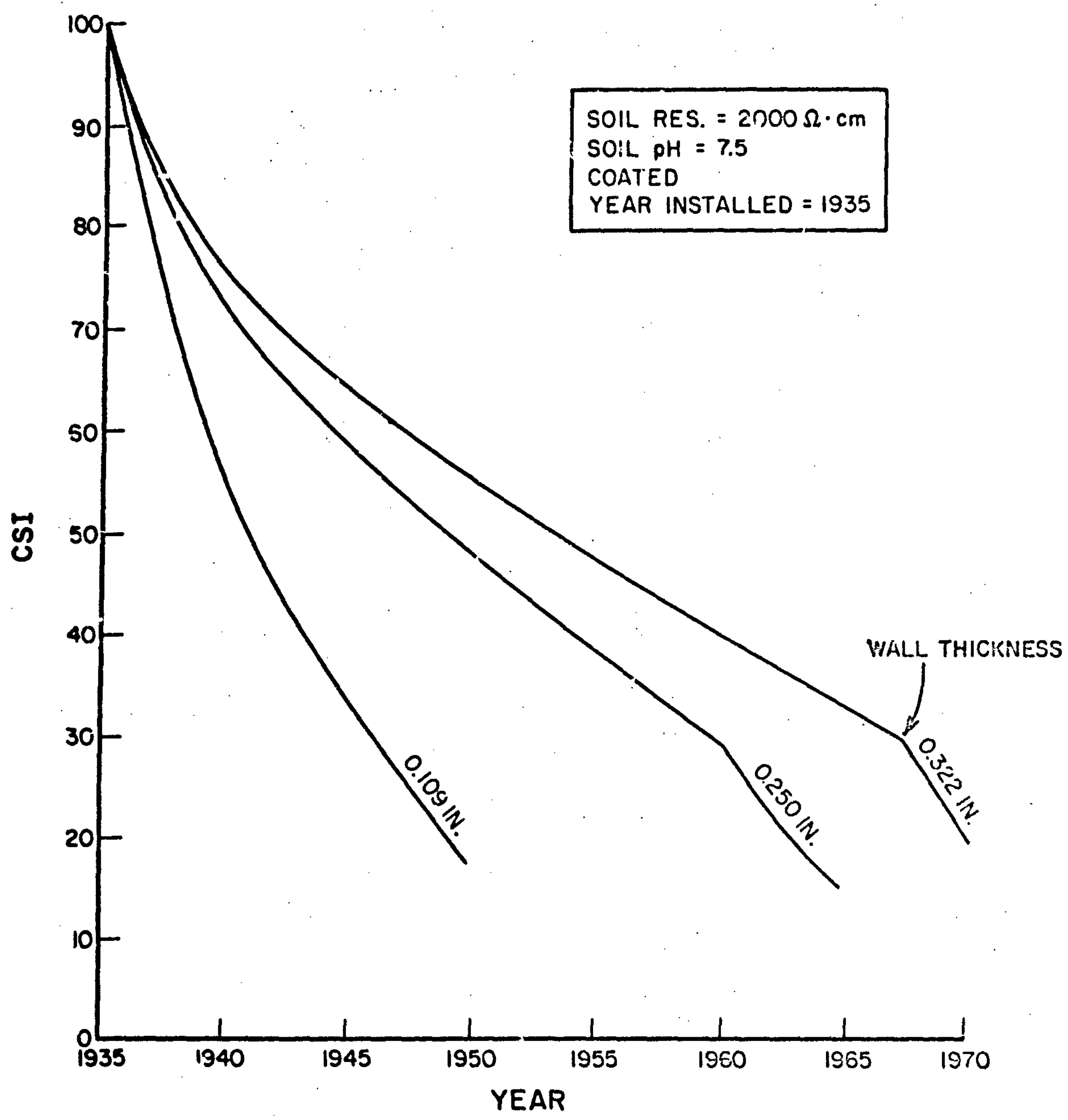


Figure 5. Prediction of CSI, effect of pipe thickness.

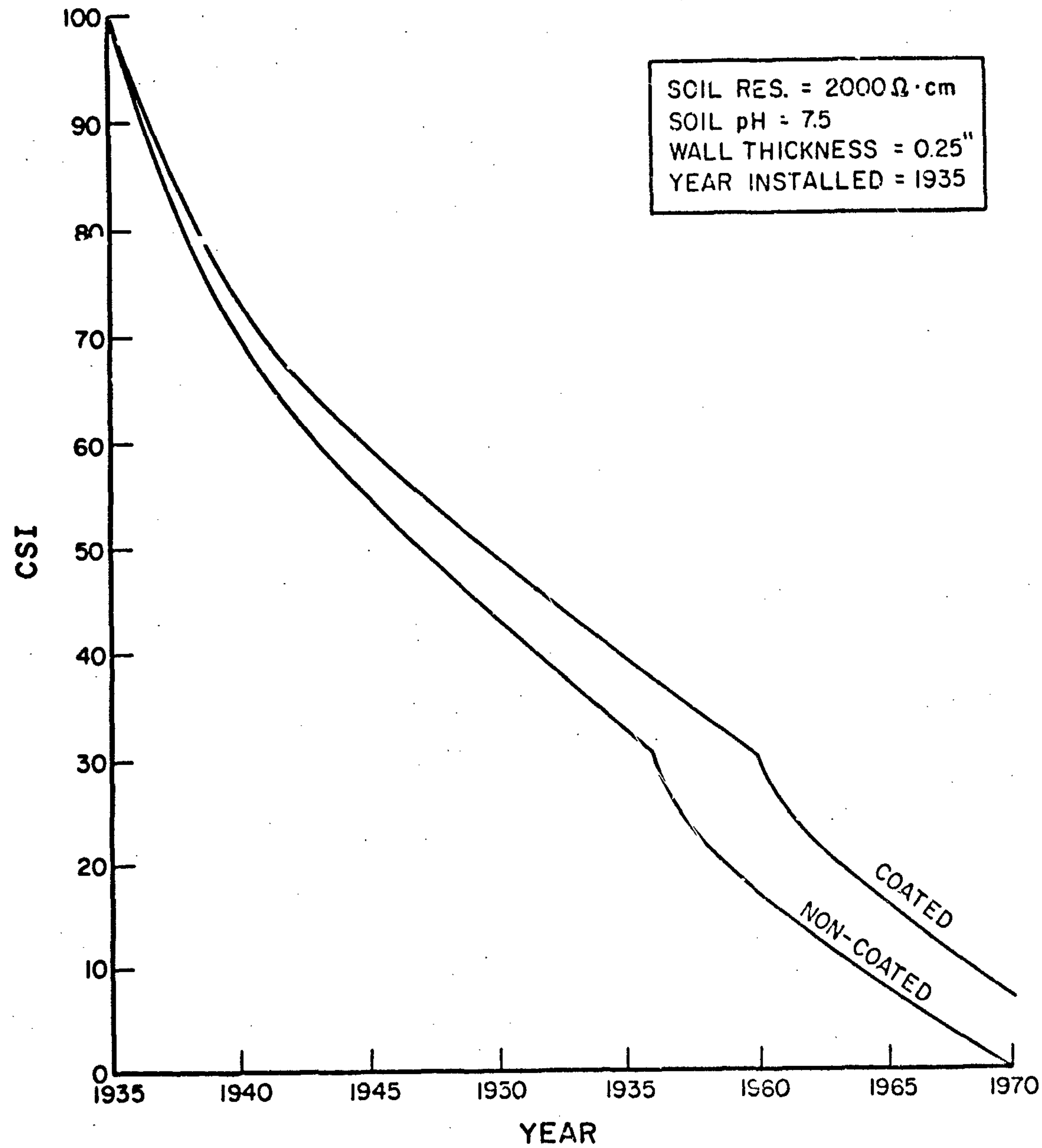


Figure 6. Prediction of CSI, effect of coating.

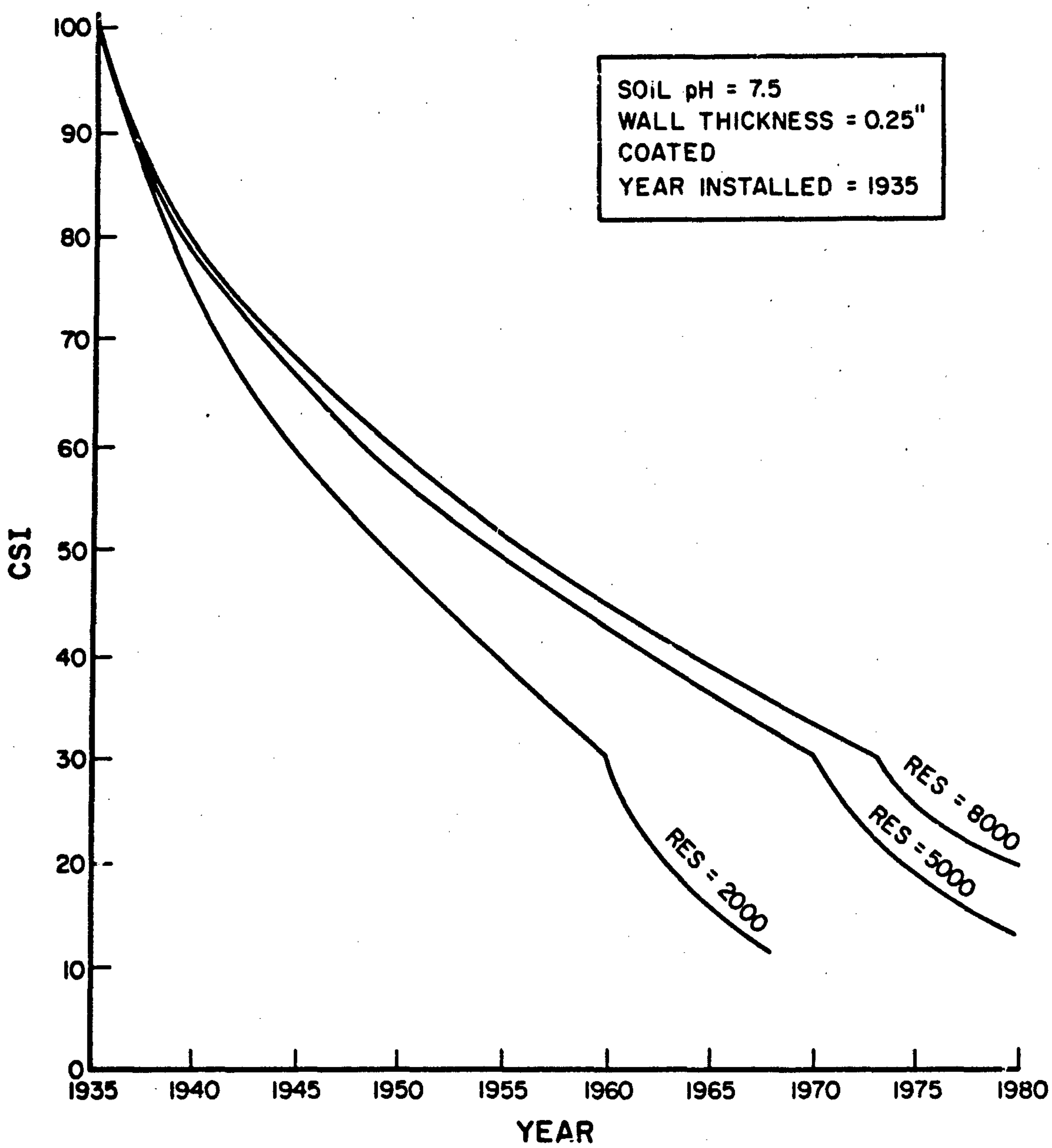


Figure 7. Prediction of CSI, effect of soil resistivity.

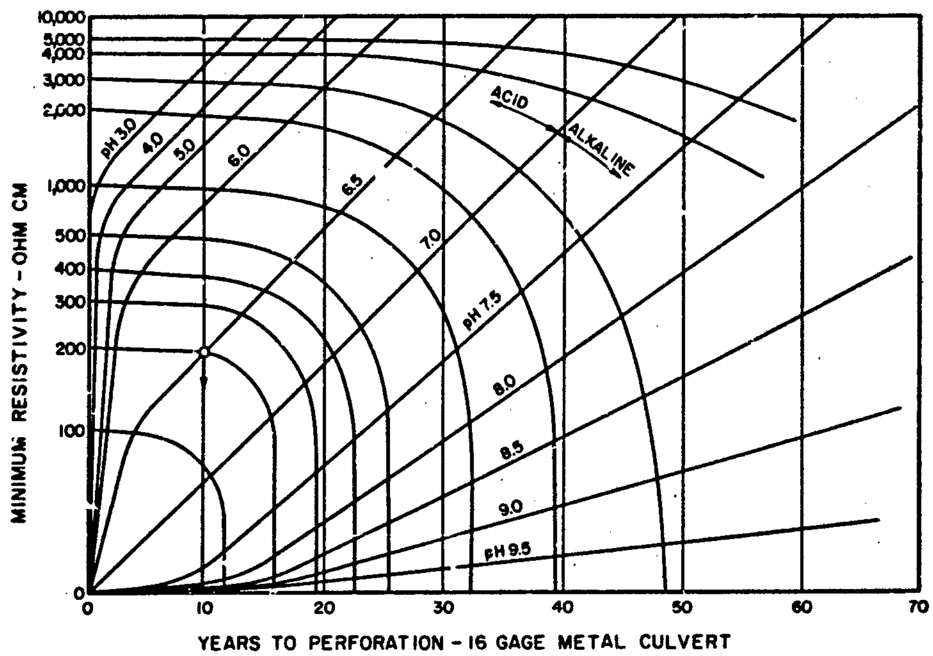


Figure 8. The effect of soil resistivity and pH on years to perforation of culverts.

measured in the laboratory on representative samples. Field measurements of soil resistivity by the four-pin method should be used only for preliminary screening. The effect of pipe thickness was incorporated in the model, assuming that the corrosion rate was proportonal to $t^{0.58}$ as observed by East Ohio[21] and Putnam.[22] The effect of "no coating," or bare, was incorporated from the New York Culvert Study;[23] the life of bare culverts was 80 percent of the live-coated culverts. The effect of moisture or saturated soil was to reduce the "years to leak" in gasoline tanks by a factor 0.66 as observed by Warren Rogers Associates. Furthermore, the effect of sulfides was to reduce the "years to leak" by a factor of 0.77. All these factors were combined to produce a predicted CSI. It should be noted that this model or the "look-up" table is preliminary and will be revised as more data are collected from actual dig-ups or by electrical polarization for underground lines.

4 CONCEPTS FOR A MANUAL CORROSION MANAGEMENT SYSTEM

The decision to repair or replace a given section of a pipeline should be based on its current CSI. Other priority factors, such as operating pressure, safety, and numerous additional considerations, enter the decision-making process. In a manual corrosion management system, only the corrosion status index is considered; all other factors are ignored because they are specific to a given site and cannot be generalized.

[21] *Procedures for Evaluating Pipeline Replacement.*

[22] J. I. Putnam

[23] *Culvert Corrosion Investigation.*

In the final decision-making process, all priority factors should be evaluated and considered. A manual system involves consideration of the following life-cycle cost analysis and management steps:

1. Network survey and analysis

   a. Inventory

   b. Leak surveys

   c. Potential surveys

2. Identify projects to be analyzed

3. Current corrosion status evaluation

   a. Sampling, pit depth evaluation

   b. Electrical polarization measurements

   c. Calculated/predicted based on age and soil corrosivity obtained from laboratory and field measurements

4. Future corrosion status and failure (leak) prediction

5. Economic analysis of M&R alternatives (present worth or annual cost analysis)

   a. Repair leaks

   b. Cathodic protection

   c. Replace with new pipe plus cathodic protection

   d. Slip line

   e. Replace with plastic pipe

6. Other priority factors evaluations

7. Maintenance–in-house/contract work/annual work plan/scope of work

8. Master Planning–new construction, military construction project data, prepare Project Description Brochure (PDB) and DD 1391.

The CSI prediction curves and tables shown in the appendix were generated by a computerized model. These curves and tables should be used in a manual system since there are too many prediction equations to use easily.

5 CONCEPTS FOR A COMPUTERIZED CORROSION MANAGEMENT SYSTEM

Preliminary work has been completed on concepts for a computerized pipe corrosion management system (PIPER)–a system designed for use by Army installations (see Figure 9). PIPER provides the maintenance decision-making tool for assigning priorities to corrosion-related maintenance and repair of underground pipes. It provides fast data storage and retrieval, pipe network definition, pipe corrosion status index, prediction of future corrosion status based on soil properties, prediction of leaks, and an economic analysis of maintenance options; all of the output can be formatted into user-defined reports. The following sections provide information on several features of PIPER.

PIPER System Database Manager

The PIPER database is a custom-designed data structure defined on a commercially available, Boeing Computer Services, computer database manager called System 2000. (System 2000 is a registered trademark of the Intel Corporation.) The data are stored in a tree structure which enables the user to retrieve information based on its connection to other data in the database. The data can be stored and retrieved through interface programs. PIPER software could be modified to operate on the Vertical Installation on Automatic Baseline (VIABLE) system–an Army-wide ADP technology–so that field implementation could be initiated and all future program developments could be written directly onto the system. VIABLE is discussed in greater detail on p 25.

PIPER Editor

The PIPER editor is a program that interfaces with the database and the user. A maintenance engineer may use this program to store inputs into the database (see Figure 9). The input consists of various data about the pipe (e.g., location, soil corrosivity, etc.). The data are entered into the editor via a terminal or cards and processed either interactively or by batch, respectively. The interactive method will do error checking and allows for immediate correction of the entered data. The batch method will process the data, produce a list of errors, and then wait for corrections before entering

the data into the database. The editor also allows the user to enter data over a number of days before it updates the database. Correction or deletion of data already in the database can also be done through the editor. Figure 10 shows a schema for the editor.

Pipe Network Definition

A pipe network is divided into pipe sections each determined by pipe size and soil properties. If one pipe runs through soil having different properties, which is often the case, it is divided into separate sections.

Pipe Corrosion Status Index—Prediction

The future corrosion status of underground lines can be predicted if the soil corrosivity is known. Various attempts have been made to determine the pit growth based on age, soil resistivity, pH, etc.[24] As more data are collected, the model may be modified by changing the subroutine containing the predictive equations. Typical predictions of future pipe corrosion status are presented in the appendix, based on the predictive model developed.

Knowing the soil properties (pH and resistivity) allows prediction of the number of years required for leaks to occur. Also, the number of cumulative leaks can be obtained based on an exponential growth curve. Figure A1 in the Appendix shows a typical table for the predicted number of leaks. Using this table, the cost of fixing the leaks may be determined, and different repair/replace strategies can be considered. Mid-course corrections can be applied if the measured CSI is different from that predicted (see Figure 11). Correction can also be applied if the actual year of first leak is known (see Figure 12).

User Defined Reports

The user may define any reports deemed useful. These reports display data from the database (i.e., location of all pipes with a CSI less than 30 and leaks) and are useful for optimizing maintenance resources. Figures 13 and 14 are two example reports.

[24] M. Romanoff; Warren Rogers Associates; *Procedures for Evaluating Pipeline Replacement;* J. L. Beaton and R. F. Stratfull; and *Culvert Corrosion Investigation.*

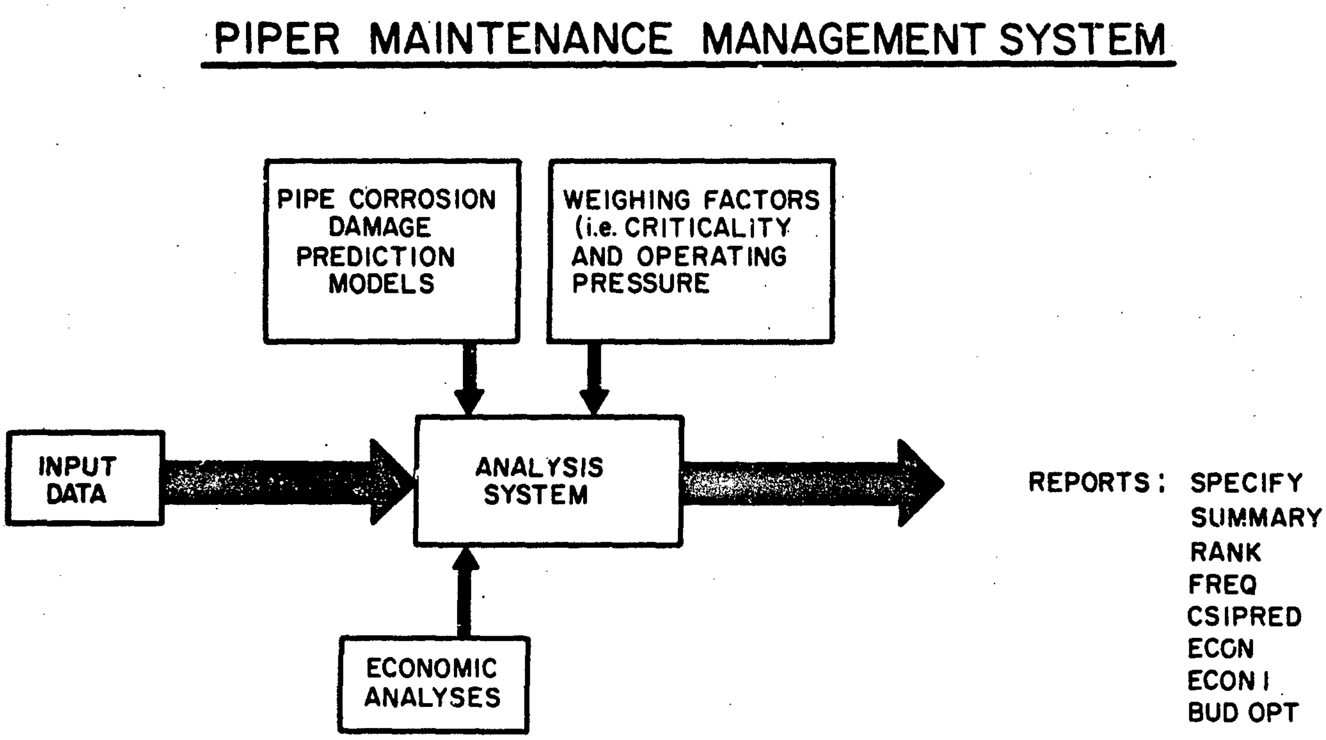


Figure 9. Pipe corrosion maintenance management system schematic.

```
INST    - INSTALLATION NAME           PID    - PIPE ID
USE     - PIPE USE                    PLN    - PIPE LENGTH
NUMSEC  - NUMBER OF SECTIONS          SN     - SECTION NUMBER
CRIT    - CRITICALITY                 SLN    - SECTION LENGTH
FROM    - FROM                        TO     - TO
YRIN    - YEAR INSTALLED              PMTRL  - PIPE MATERIAL
CMTRL   - COATING MATERIAL            PROT   - PROTECTION
DEPTH   - BURIED DEPTH                DIA    - PIPE DIAMETER OD
WLTHK   - WALL THICKNESS              OPRES  - OPERATING PRESSURE
NUMVLV  - NUMBER OF VALVES            JNTS   - TYPE OF JOINTS
RES     - SOIL RESISTIVITY            PH     - SOIL PH
CHL     - SOIL CHLORIDES              SULF   - SOIL SULFIDES
MST     - SOIL MOISTURE               GC     - GALVANIC CORROSION
INTER   - INTERFERENCE                FRSTLK - YEAR OF FIRST LEAK
LKINT   - LEAK RECORD INTEGRITY       DTCMNT - DATE OF COMMENTS
CMMT    - COMMENT                     VID    - VALVE ID
VTYPE   - VALVE TYPE                  VLOC   - VALVE LOCATION
RCTID   - RECTIFIER ID                RCTLOC - RECTIFIER LOCATION
OPSTAT  - OPERATIONAL STATUS          STID   - STATION ID
STLOC   - STATION LOCATION            PSYR   - POTENTIAL SURVEY YEAR

 ENTER [CR] TO CONTINUE OR [QUIT] TO EXIT
I>
PSLOC   - POTENTIAL SURVEY LOCATION   VLPROT - VALUE OF PROTECTION
DTLK    - DATE LEAK DETECTED          TYPELK - TYPE OF LEAK
LKLOC   - LOCATION OF LEAK            DTRP   - DATE OF REPAIR
TYPERP  - TYPE OF REPAIR              YRPIT  - YEAR PIT
PITDP   - AVERAGE PIT DEPTH           MCSIDT - MEASURED CSI DATE
MECSI   - MEASURED ELECTRICAL CSI
```

Figure 10. Schema–input parameters for the computerized system PIPER.

PRIORITY RANKING   REPORT DATE: 04/18/83

ORDER	PIPE - ID	SEC #	CSI	PRESSURE
0	CERL-D	01	0	60.0000
0	CERL-D	02	0	60.0000
5	CERL-D	03	5	60.0000
13	CERL-D	04	13	60.0000
15	CERL-D	05	15	60.0000

Figure 11. Typical priority ranking report.

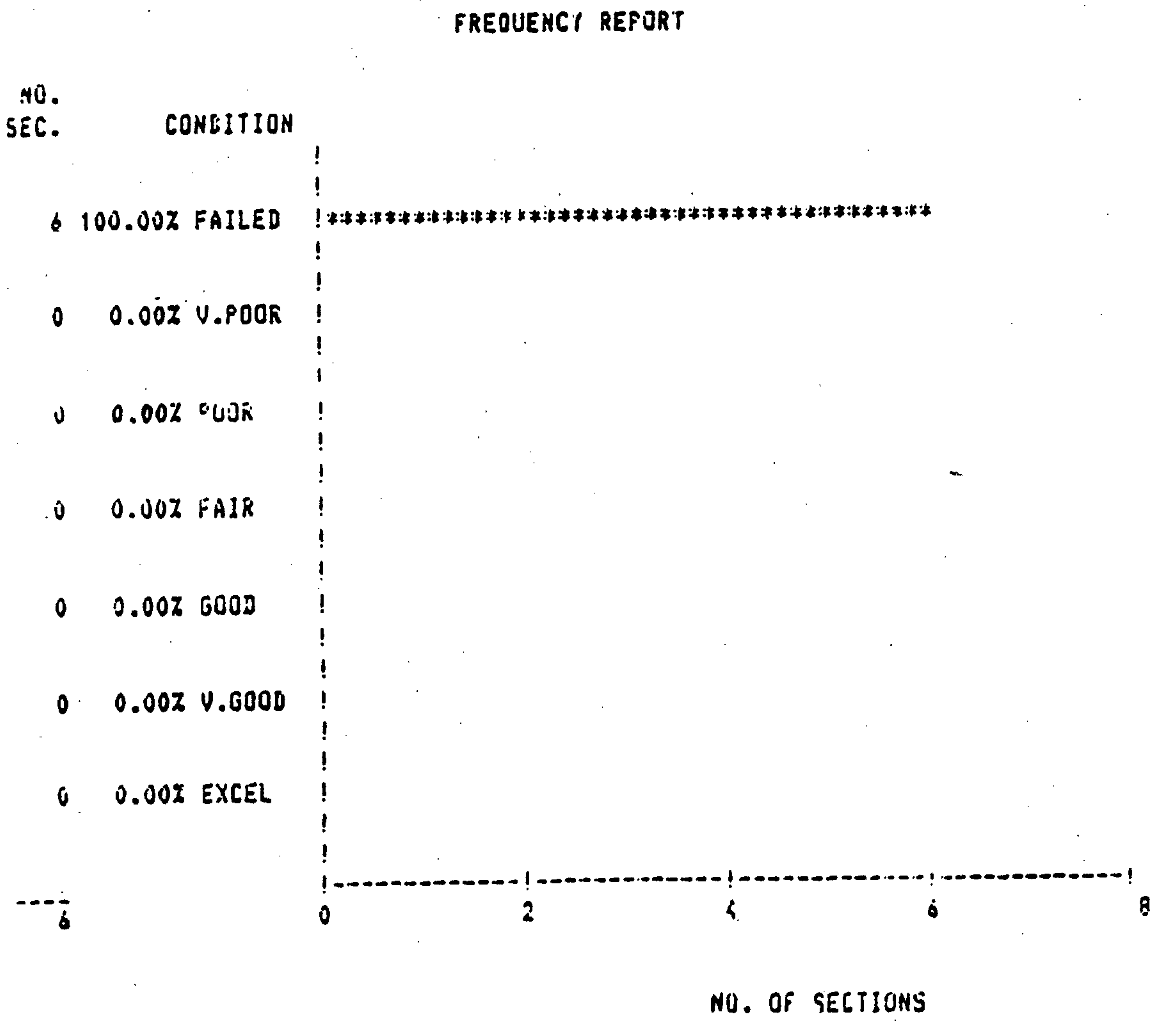
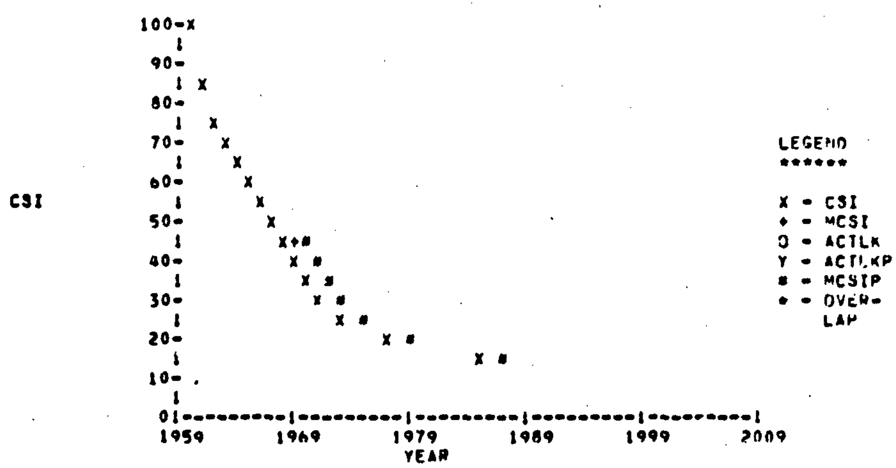


Figure 12. Typical frequency report.

CSI PREDICTION REPORT
REPORT DATE 06/15/83

PIPE ID	GAS J	SECTION NUMBER	G
SOIL RESISTIVITY	7000.00	SOIL PH	6.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.1540
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1971		
ACTUAL FIRST LEAK			



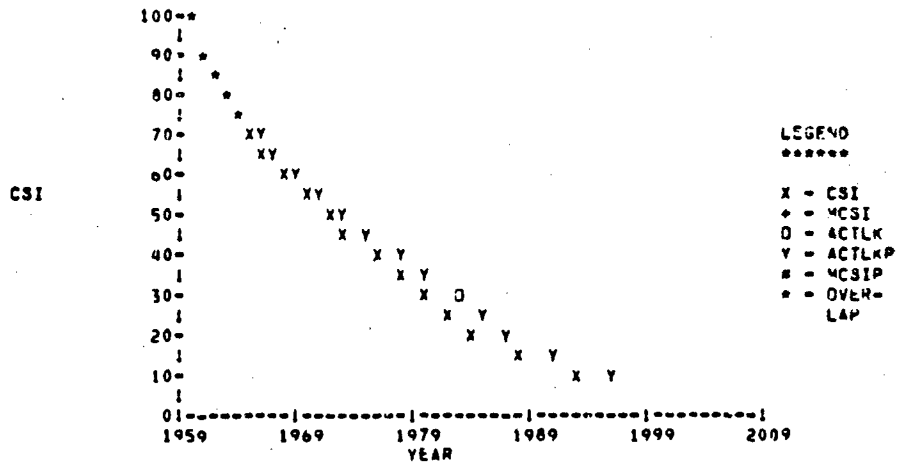
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	83	0	0
1962	74	0	0
1963	67	0	0
1964	61	0	0
1965	56	0	0
1966	51	0	0
1967	46	0	0
1968	42	0	0
1969	38	0	0
1970	34	0	0
1971	30	1	1
1972	26	1	2
1973	24	1	3
1974	23	1	4
1975	22	2	6
1976	21	1	7
1977	20	2	9
1978	19	2	11
1979	19	1	12
1980	18	2	14
1981	17	2	16
1982	17	2	18
1983	16	3	21
1984	16	2	23
1985	15	3	26
1986	15	2	28
1987	15	3	31
1988	14	3	34
1989	14	4	38
1990	13	3	41
1991	13	4	45

Figure 13. CSI prediction report–midcourse correction.

CSI PREDICTION REPORT
REPORT DATE 06/15/83

PIPE ID	GAS J	SECTION NUMBER	F
SOIL RESISTIVITY	5000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.1540
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1980		
ACTUAL FIRST LEAK	1983		



GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	88	0	0
1962	82	0	0
1963	77	0	0
1964	72	0	0
1965	69	0	0
1966	65	0	0
1967	62	0	0
1968	59	0	0
1969	56	0	0
1970	53	0	0
1971	51	0	0
1972	48	0	0
1973	45	0	0
1974	43	0	0
1975	41	0	0
1976	38	0	0
1977	36	0	0
1978	34	0	0
1979	32	0	0
1980	30	1	1
1981	26	1	2
1982	23	2	4
1983	22	2	6
1984	20	3	9
1985	19	3	12
1986	17	4	16
1987	16	5	21
1988	15	6	27
1989	14	7	34
1990	13	9	43
1991	12	11	54
1992	11	13	67
1993	10	15	82

Figure 14. CSI prediction report - first leak correction.

Economic Analysis

PIPER can provide an economic analysis by inputting inflation and interest rates. Typical alternative maintenance strategies, such as repair leaks, replace with plastic pipe, replace with coated pipe with cathodic protection, and slipline, can be evaluated, and "what if" questions can be answered as shown in Figures 15 and 16. Then a repair/replace decision can be made.

Other user-oriented reports such as annual work plan, 5-year work plan, budget optimization, etc., could also be formatted.

Computerization is not absolutely necessary; a manual system could achieve some of the objectives of systematic management. However, the computerized version would have the advantages of data storage and manipulation, fast retrieval, provision of a complete inventory of underground pipes and their location, provision of present and future corrosion status summary, and provision of an easy means of economic analysis and budget planning. Its disadvantages would be costs of initial investment, training, and implementation; therefore, the relative economics of computerization must be evaluated.

VIABLE

VIABLE is an integrated network consisting of five regional centers, with 70 data-processing installations to handle 50 to 600 terminals at each Army installation. Army Automation Management and Systems Development Responsibilities are specified in Army Regulation AR 18-1. The U.S. Army Computer Systems Command is the responsible agency for the integrated Facilities System (IFS). IFS is a standard Army multi-command managment information system (STAMMIS) developed to support life-cycle management of real property resources. At the installation level, it will support inventory management, work management, cost accounting, and resource management. IFS is being redesigned by the U.S. Army Facility Engineer Support Agency (FESA) for full interactivity on VIABLE. At present, the basic package of IFS redesign (IFS-R) includes DEH management functions such as real property inventory, job cost accounting, work management, and contract management. Other functions can be added to the basic package. The first IFS-R package for redesign has 31 functions, including contract management, service orders, work requests, planning and estimating, scheduling analysis, cost computing, inspection program, facility utilization, and executive level information. As planned, the utilities branch will have one terminal and one printer to have access to the VIABLE.

It is the policy of the Facilities Engineering Division, Office of the Chief of Engineers,[25] that systems software be developed to operate, without change, on the VIABLE hardware. VIABLE will be used to support all base operations information needs for the DEH. Since IFS-R is to be the initial base for development of the RPMA (Real Property Maintenance Activity) program, all systems which are designed to identify RPMA requirements, except major construction, will be designed to feed requirements into IFS-R. Future developments could also be programmed to operate on IFS-Redesign in accordance with Army guidance.

6 CONCLUSIONS AND RECOMMENDATIONS

Review of the state of the art of pipeline corrosion assessment has determined that current techniques must be improved to become nondestructive, more accurate and economical, and less personnel-intensive. Initial laboratory tests have validated the conceptual feasibility of using the polarization decay principle as a nondestructive technique to determine the corrosion status of underground pipes without digging.

Two new concepts for evaluating pipeline repair/replace decisions have been developed. A corrosion status index allows the maintenance engineer to quantify the condition of pipelines, and computerized "look-up" tables allow prediction of corrosion damage and leaks.

Concepts for the pipe corrosion management system (PIPER), a computerized procedure for determining repair/replace options for corroded underground pipes, have been developed. This system has the following advantages:

1. Complete up-to-date inventory of undergound pipes with locations

2. Data storage and fast retrieval

[25] Disposition Form, dated 16 March 1983, Subject: "Division Policy on System Development Efforts."

REPORT DATE - 83/10/21

COMPARISON OF M&R ALTERNATIVES
GAS E
SECTION M

INFLATION RATE .00 PERCENT
ANALYSIS PERIOD - 5 YEARS INTEREST RATE 10.00 PERCENT

ALTERNATIVE	DESCRIPTION	NET PRESENT COST
A	REPAIR LEAKS	14453
B	REPLACE WITH PLASTIC PIPE	46486
C	REPLACE WITH COATED PIPE PLUS CATHODIC PROTECTION	53627

DETAILED COMPARISON OF M&R ALTERNATIVES

YEAR	ALT A COST	ALT A PRES COST	ALT B COST	ALT B PRES COST	ALT C COST	ALT C PRES COST
0 (FY83)	300	300	300	300	300	300
1 (FY84)	1500	1363	1500	1363	1500	1363
2 (FY85)	2400	1983	2400	1983	2400	1983
3 (FY86)	3300	2479	3300	2479	3300	2479
4 (FY87)	5100	3483	60000	40900	70000	47810
5 (FY88)	7800	4843	0	0	500	310
TOTAL	20400	14453	67500	47107	78000	54247
SALVAGE	0	0	1000	620	1000	620
PRES WORTH		14453		46486		53626

Figure 15. Typical economic analysis report (5-year period).

REPORT DATE - 83/10/21

COMPARISON OF M&R ALTERNATIVES
GAS E
SECTION M

INFLATION RATE .00 PERCENT
ANALYSIS PERIOD - 10 YEARS INTEREST RATE 10.00 PERCENT

ALTERNATIVE	DESCRIPTION	NET PRESENT COST
C	REPLACE WITH COATED PIPE PLUS CATHODIC PROTECTION	40707
B	REPLACE WITH PLASTIC PIPE	46722
A	REPAIR LEAKS	80947

DETAILED COMPARISON OF M&R ALTERNATIVES

YEAR	ALT A COST	ALT A PRES COST	ALT B COST	ALT B PRES COST	ALT C COST	ALT C PRES COST
0 (FY83)	300	300	300	300	300	300
1 (FY84)	1500	1363	1500	1363	1500	1363
2 (FY85)	2400	1983	2400	1983	2400	1983
3 (FY86)	3300	2479	3300	2479	3300	2479
4 (FY87)	5100	3483	60000	40980	50000	34150
5 (FY88)	7800	4843	0	0	750	465
6 (FY89)	11400	6435	0	0	0	0
7 (FY90)	17400	8928	0	0	0	0
8 (FY91)	25800	12035	0	0	750	349
9 (FY92)	39000	16539	0	0	0	0
10 (FY93)	58500	22554	0	0	0	0
TOTAL	172500	80946	67500	47107	59000	41092
SALVAGE	0	0	1000	385	1000	385
PRES WORTH		80946		46721		40707

Figure 16. Typical economic analysis report (10-year period).

3. Present and future corrosion status summary

4. Economic analysis and budget planning in user-oriented format.

Its disadvantages will be costs associated with initial investment, training, and implementation.

Concepts have been developed for a manual system that could achieve some of these objectives, but it would have less power and flexibility. The relative economics of both systems must therefore be quantified.

It is recommended that research into developing a manual system for making underground line repair/replace decisions be continued and that the projected costs associated with implementing a computerized system be determined.

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APPENDIX: PRELIMINARY CSI PREDICTIONS

The CSI Prediction Reports shown in Figures A1 through A15 each consist of a CSI vs. time curve and a corresponding graph table listing CSIs and number of leaks. An important concern of pipe maintenance management is to determine when the leaks begin to occur. Definition of the CSI prediction model states that the first leak will occur at CSI = 30, as shown in each table.

To predict the average number of "years to leak," look up the wall thickness corresponding to the pipe size (Table A1). (Most Army gas lines are schedule 40; however, schedule 80 pipes also exist.) The curves are based on nominal pipe sizes 1, 2, and 3 schedule 40. For this example, a neutral pH of 7 is used. Look for the corresponding curve for minimum soil resistivity (laboratory measurements). For values in between those given, assume linear interpolation as a first approximation. Look up the number of "years to leak" and total "number of leaks."

If the pipe is bare, then multiply "year to leak" by 0.8. If the soil is saturated, then multiply "year to leak" by a factor of 0.66. If the soil contains sulfides in excess of 50 ppm, multiply by a "year to leak" factor of 0.77.

If a multiplier (0.8, 0.66, 0.77) is used to determine the "year to leak," disregard the corresponding cumulative leak values in the table and refer to Figure A1 to predict the number of leaks.

As an example, assume a pipe with a nominal size of 1 in. lies in a soil which has a resistivity of 3000 ohm.cm and a pH of 7. In Table A1, a nominal pipe size of 1 in. (schedule 40) corresponds to a wall thickness of 0.133 in., which is considered in the first 10 prediction reports. Referring to the report which deals with a soil resistivity of 3000 ohm.cm and a soil pH of 7, the first leak should occur 14 years after pipe installation; the corresponding cumulative leaks will occur thereafter.

This example assumes that the pipe is coated; however, for a bare pipe, the first leak should occur in (14 years) X (0.8) = 11.2 years. Therefore, a bare 1-in. pipe in a saturated soil, with resistivity = 3000 ohm.cm, pH = 7.0, and sulfides = 60 ppm, will begin to leak in:

$$(14 \text{ years}) \times (0.8) \times (0.66) \times (0.77) = 5.7 \text{ years}$$

Referring to Figure A4, this pipe should have about 20 leaks within 5 years after the occurrence of the first leak.

Table A1

ANSI Pipe Schedules

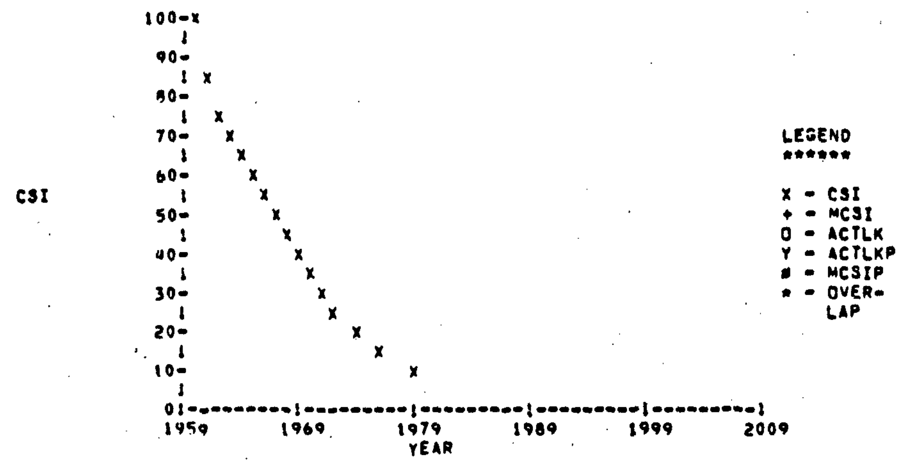
Nominal Pipe Size	Actual Pipe OD (in inches)	Wall Thickness (in inches) Schedule 40	Wall Thickness (in inches) Schedule 80
1/2	0.84	0.109	0.147
3/4	1.050	0.113	0.154
1	1.315	0.133	0.179
1-1/4	1.660	0.140	0.191
1-1/2	1.900	0.145	0.200
2	2.375	0.154	0.218
2-1/2	2.875	0.203	0.276
3	3.5	0.216	0.300
3-1/2	4.0	0.226	0.318
4	4.5	0.237	0.337
5	5.563	0.258	0.375
6	6.625	0.280	0.432
8	8.625	0.322	0.500

The guide specification for gas distribution lines is CEGS-02711.

CSI PREDICTION REPORT
REPORT DATE 06/13/83

PIPE ID GAS E SECTION NUMBER B

SOIL RESISTIVITY 1000.00 SOIL PH 7.00
COATING MATERIAL COAL TAR WALL THICKNESS .1330
YEAR INSTALLED 1960
PREDICTED FIRST LEAK 1971
ACTUAL FIRST LEAK



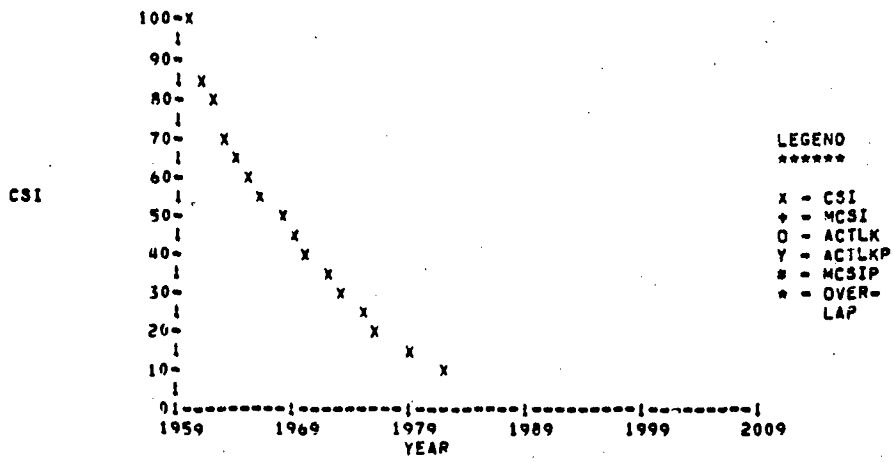
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	83	0	0
1962	74	0	0
1963	67	0	0
1964	61	0	0
1965	56	0	0
1966	51	0	0
1967	46	0	0
1968	42	0	0
1969	38	0	0
1970	34	0	0
1971	30	1	1
1972	25	2	3
1973	23	2	5
1974	20	5	10
1975	17	8	18
1976	15	11	29
1977	13	17	46
1978	11	25	71
1979	9	38	109

Figure A1. CSI prediction report for Section B (wall thickness .1330).

CSI PREDICTION REPORT
REPORT DATE 06/13/83

PIPE ID	GAS E	SECTION NUMBER	D
SOIL RESISTIVITY	3000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.1330
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1973		
ACTUAL FIRST LEAK			



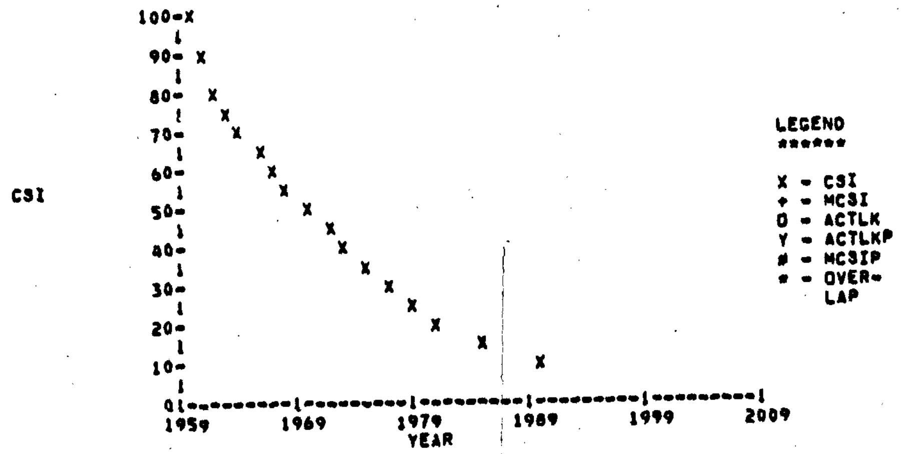
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	84	0	0
1962	76	0	0
1963	70	0	0
1964	65	0	0
1965	60	0	0
1966	55	0	0
1967	51	0	0
1968	47	0	0
1969	43	0	0
1970	40	0	0
1971	36	0	0
1972	33	0	0
1973	30	1	1
1974	26	2	3
1975	23	2	5
1976	20	3	8
1977	18	5	13
1978	17	7	20
1979	15	9	29
1980	13	12	41
1981	12	18	59
1982	10	24	83

Figure A2. CSI prediction report for Section D (wall thickness .1330).

CSI PREDICTION REPORT
REPORT DATE 06/07/83

PIPE ID	GAS E	SECTION NUMBER	F
SOIL RESISTIVITY	5000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.1330
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1977		
ACTUAL FIRST LEAK			



GRAPH TABLE

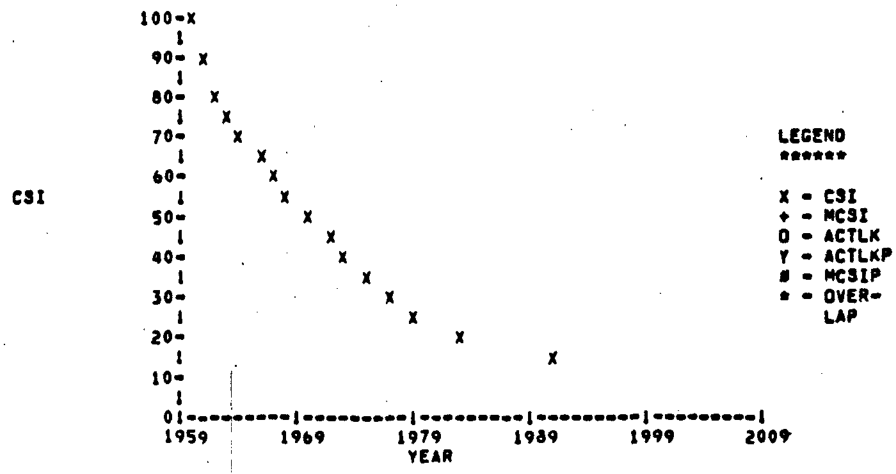
CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	86	0	0
1962	80	0	0
1963	74	0	0
1964	70	0	0
1965	66	0	0
1966	62	0	0
1967	58	0	0
1968	55	0	0
1969	52	0	0
1970	49	0	0
1971	46	0	0
1972	43	0	0
1973	40	0	0
1974	37	0	0
1975	35	0	0
1976	32	0	0
1977	30	1	1
1978	26	1	2
1979	23	2	4
1980	22	2	6
1981	20	3	9
1982	19	3	12
1983	17	4	16
1984	16	5	21
1985	15	6	27
1986	14	7	34
1987	13	9	43
1988	12	11	54
1989	11	13	67
1990	10	15	82

Figure A3. CSI prediction report for Section F (wall thickness .1330).

CSI PREDICTION REPORT
REPORT DATE 06/07/83

PIPE ID GAS E SECTION NUMBER H

SOIL RESISTIVITY 7000.00 SOIL PH 7.00
COATING MATERIAL COAL TAR WALL THICKNESS .1330
YEAR INSTALLED 1960
PREDICTED FIRST LEAK 1977
ACTUAL FIRST LEAK



GRAPH TABLE

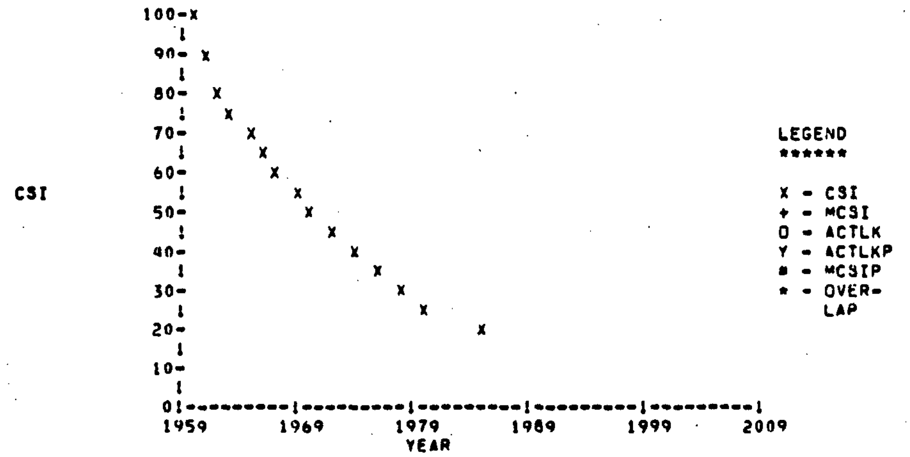
CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	86	0	0
1962	80	0	0
1963	74	0	0
1964	70	0	0
1965	66	0	0
1966	62	0	0
1967	58	0	0
1968	55	0	0
1969	52	0	0
1970	49	0	0
1971	46	0	0
1972	43	0	0
1973	40	0	0
1974	37	0	0
1975	35	0	0
1976	32	0	0
1977	30	1	1
1978	26	1	2
1979	24	1	3
1980	23	1	4
1981	22	2	6
1982	21	1	7
1983	20	2	9
1984	19	2	11
1985	19	1	12
1986	18	2	14
1987	17	2	16
1988	17	2	18
1989	16	3	21
1990	16	2	23
1991	15	3	26
1992	15	2	28
1993	15	3	31
1994	14	3	34
1995	14	4	38
1996	13	3	41
1997	13	4	45

Figure A4. CSI prediction report for Section H (wall thickness .1330).

CSI PREDICTION REPORT
REPORT DATE 06/13/83

PIPE ID GAS E SECTION NUMBER J

SOIL RESISTIVITY	9000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.1330
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1978		
ACTUAL FIRST LEAK			



GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	87	0	0
1962	80	0	0
1963	75	0	0
1964	71	0	0
1965	67	0	0
1966	63	0	0
1967	60	0	0
1968	56	0	0
1969	53	0	0
1970	50	0	0
1971	47	0	0
1972	45	0	0
1973	42	0	0
1974	39	0	0
1975	37	0	0
1976	35	0	0
1977	32	0	0
1978	30	1	1
1979	26	1	2
1980	25	1	3
1981	23	1	4
1982	23	1	5
1983	22	1	6
1984	21	1	7
1985	20	1	8
1986	20	1	9
1987	20	1	10
1988	19	1	11
1989	19	1	12
1990	18	1	13
1991	18	1	14
1992	18	1	15
1993	17	1	16
1994	17	1	17
1995	17	1	18
1996	17	1	19
1997	16	1	20
1998	16	1	21

Figure A5. CSI prediction report for Section J (wall thickness .1330).

CSI PREDICTION REPORT
REPORT DATE 06/21/83

```
PIPE ID                 GAS G          SECTION NUMBER  B

SOIL RESISTIVITY         1000.00       SOIL PH           7.00
COATING MATERIAL        COAL TAR       WALL THICKNESS          .2160
YEAR INSTALLED          1960
PREDICTED FIRST LEAK    1977
ACTUAL FIRST LEAK
```

```
            100-X
               I
             90- X
               I
             80-  X
               I   X
             70-    X
               I      X
             60-       X
CSI            I        X
             50-          X
               I            X
             40-             X
               I               X
             30-                 X
               I                  X
             20-                    X
               I                      X
             10-                         X
               I
              0I---------I---------I---------I---------I---------I
              1959      1969      1979      1989      1999      2009
                                  YEAR
```

```
LEGEND
******

X - CSI
+ - MCSI
J - ACTLK
Y - ACTLKP
# - MCSIP
* - OVER-
    LAP
```

GRAPH TABLE

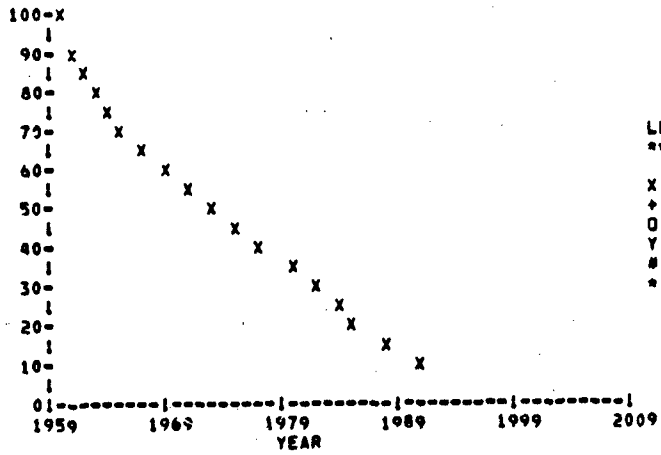
CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	86	0	0
1962	80	0	0
1963	74	0	0
1964	70	0	0
1965	66	0	0
1966	62	0	0
1967	58	0	0
1968	55	0	0
1969	52	0	0
1970	49	0	0
1971	46	0	0
1972	43	0	0
1973	40	0	0
1974	37	0	0
1975	35	0	0
1976	32	0	0
1977	30	1	1
1978	25	2	3
1979	23	2	5
1980	20	5	10
1981	17	8	18
1982	15	11	29
1983	13	17	46
1984	11	25	71
1985	9	38	109

Figure A6. CSI prediction report for Section B (wall thickness .2160).

CSI PREDICTION REPORT
REPORT DATE 06/21/83

PIPE ID	GAS G	SECTION NUMBER	D
SOIL RESISTIVITY	3000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.2160
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1982		
ACTUAL FIRST LEAK			

CSI



LEGEND
******

X - CSI
+ - MCSI
O - ACTLK
Y - ACTLKP
- MCSIP
* - OVER-
LAP

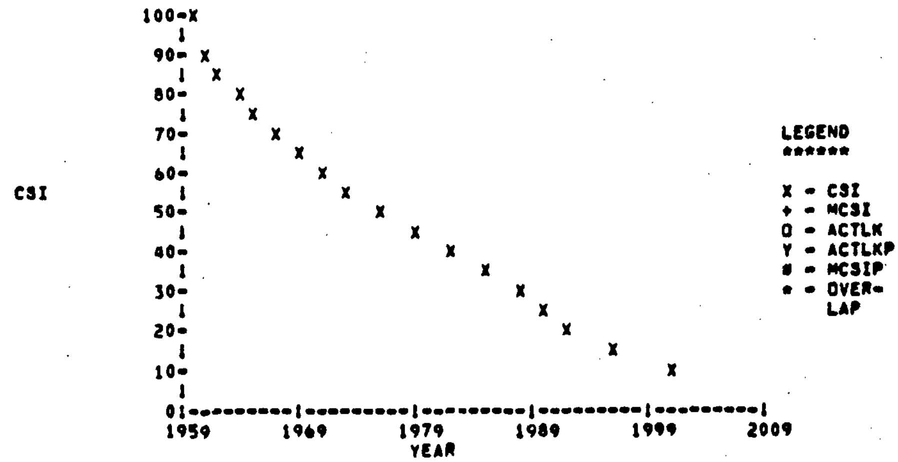
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	88	0	0
1962	83	0	0
1963	78	0	0
1964	74	0	0
1965	70	0	0
1966	67	0	0
1967	64	0	0
1968	61	0	0
1969	58	0	0
1970	56	0	0
1971	53	0	0
1972	51	0	0
1973	48	0	0
1974	46	0	0
1975	44	0	0
1976	42	0	0
1977	40	0	0
1978	38	0	0
1979	36	0	0
1980	34	0	0
1981	32	0	0
1982	30	1	1
1983	26	2	3
1984	23	2	5
1985	20	3	8
1986	18	5	13
1987	17	7	20
1988	15	9	29
1989	13	12	41
1990	12	18	59
1991	10	24	83

Figure A7. CSI prediction report for Section D (wall thickness .2160).

CSI PREDICTION REPORT
REPORT DATE 06/21/83

PIPE ID	GAS G	SECTION NUMBER	F
SOIL RESISTIVITY	5000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.2160
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1988		
ACTUAL FIRST LEAK			



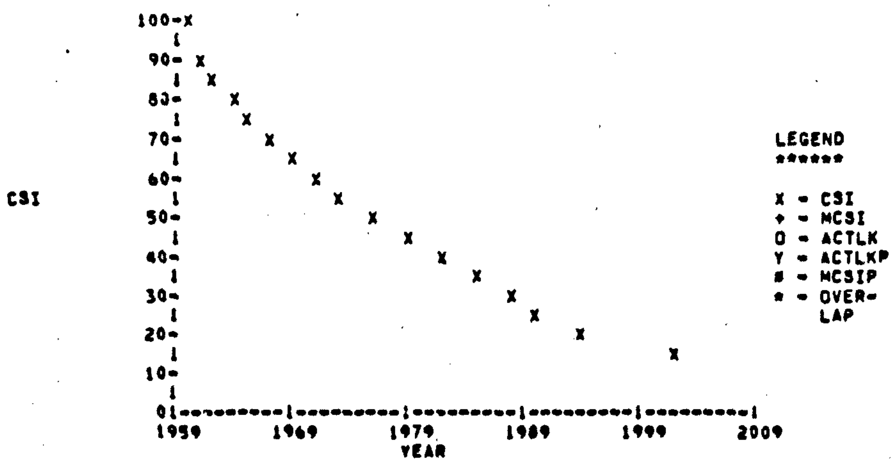
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	93	0	0
1962	85	0	0
1963	81	0	0
1964	77	0	0
1965	74	0	0
1966	71	0	0
1967	69	0	0
1968	66	0	0
1969	64	0	0
1970	61	0	0
1971	59	0	0
1972	57	0	0
1973	55	0	0
1974	53	0	0
1975	51	0	0
1976	49	0	0
1977	48	0	0
1978	46	0	0
1979	44	0	0
1980	42	0	0
1981	41	0	0
1982	39	0	0
1983	38	0	0
1984	36	0	0
1985	34	0	0
1986	33	0	0
1987	31	0	0
1988	30	1	1
1989	26	1	2
1990	23	2	4
1991	22	2	6
1992	20	3	9
1993	19	3	12
1994	17	4	16
1995	16	5	21
1996	15	6	27
1997	14	7	34
1998	13	9	43
1999	12	11	54
2000	11	13	67
2001	10	15	82

Figure A8. CSI prediction report for Section F (wall thickness .2160).

CSI PREDICTION REPORT
REPORT DATE 06/21/83

PIPE ID	GAS G	SECTION NUMBER	H
SOIL RESISTIVITY	7000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.2160
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1988		
ACTUAL FIRST LEAK			



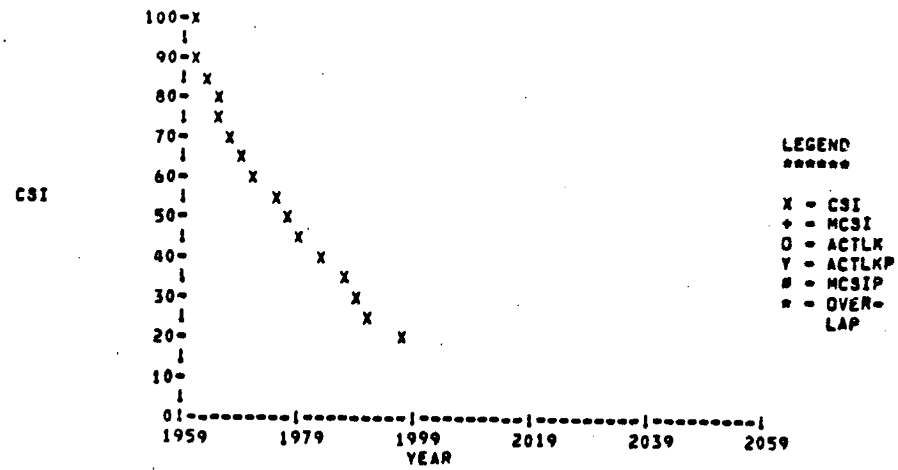
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	90	0	0
1962	85	0	0
1963	81	0	0
1964	77	0	0
1965	74	0	0
1966	71	0	0
1967	69	0	0
1968	66	0	0
1969	64	0	0
1970	61	0	0
1971	59	0	0
1972	57	0	0
1973	55	0	0
1974	53	0	0
1975	51	0	0
1976	49	0	0
1977	48	0	0
1978	46	0	0
1979	44	0	0
1980	42	0	0
1981	41	0	0
1982	39	0	0
1983	38	0	0
1984	36	0	0
1985	34	0	0
1986	33	0	0
1987	31	0	0
1988	30	1	1
1989	26	1	2
1990	24	1	3
1991	23	1	4
1992	22	2	6
1993	21	1	7
1994	20	2	9
1995	19	2	11
1996	19	1	12
1997	18	2	14
1998	17	2	16
1999	17	2	18
2000	16	3	21
2001	16	2	23
2002	15	3	26
2003	15	2	28
2004	15	3	31
2005	14	3	34
2006	14	4	38
2007	13	3	41
2008	13	4	45

Figure A9. CSI prediction report for Section H (wall thickness .2160).

CSI PREDICTION REPORT
REPORT DATE 06/21/83

PIPE ID	GAS G	SECTION NUMBER	J
SOIL RESISTIVITY	9000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.2160
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1989		
ACTUAL FIRST LEAK			



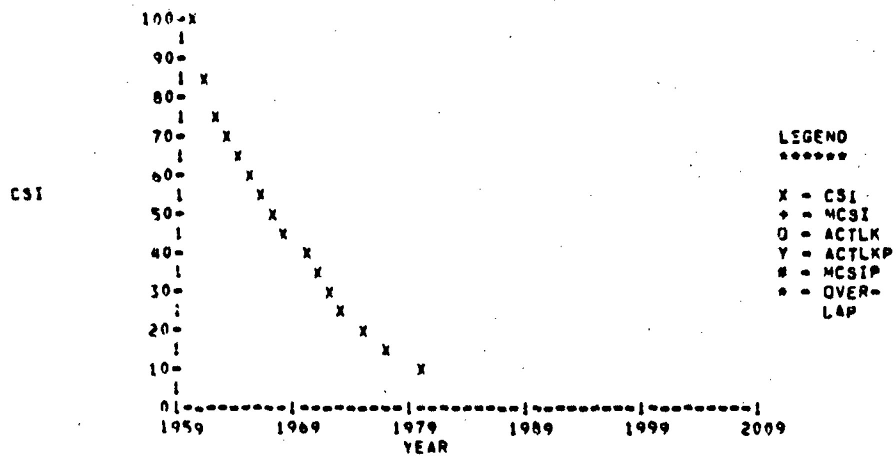
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	90	0	0
1962	85	0	0
1963	81	0	0
1964	78	0	0
1965	75	0	0
1966	72	0	0
1967	69	0	0
1968	67	0	0
1969	64	0	0
1970	62	0	0
1971	60	0	0
1972	58	0	0
1973	56	0	0
1974	54	0	0
1975	52	0	0
1976	50	0	0
1977	49	0	0
1978	47	0	0
1979	45	0	0
1980	44	0	0
1981	42	0	0
1982	40	0	0
1983	39	0	0
1984	37	0	0
1985	36	0	0
1986	34	0	0
1987	33	0	0
1988	31	0	0
1989	30	1	1
1990	26	1	2
1991	25	1	3
1992	23	1	4
1993	23	1	5
1994	22	1	6
1995	21	1	7
1996	20	1	8
1997	20	1	9
1998	20	1	10
1999	19	1	11
2000	19	1	12
2001	18	1	13
2002	18	1	14
2003	18	1	15
2004	17	1	16
2005	17	1	17
2006	17	1	18
2007	17	1	19
2008	16	1	20
2009	16	1	21

Figure A10. CSI prediction report for Section J (wall thickness .2160).

CSI PREDICTION REPORT
REPORT DATE 06/15/83

PIPE ID	GAS J	SECTION NUMBER	B
SOIL RESISTIVITY	1000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.1540
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1972		
ACTUAL FIRST LEAK			



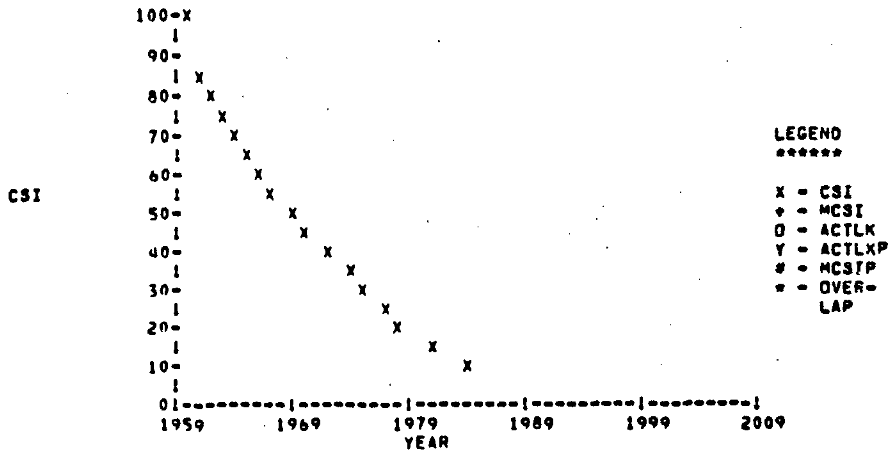
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	83	0	0
1962	75	0	0
1963	69	0	0
1964	63	0	0
1965	58	0	0
1966	53	0	0
1967	49	0	0
1968	45	0	0
1969	41	0	0
1970	37	0	0
1971	33	0	0
1972	30	1	1
1973	25	2	3
1974	23	2	5
1975	20	5	10
1976	17	8	18
1977	15	11	29
1978	13	17	46
1979	11	25	71
1980	9	38	109

Figure A11. CSI prediction report for Section B (wall thickness .1540).

CSI PREDICTION REPORT
REPORT DATE 06/15/83

PIPE ID	GAS J	SECTION NUMBER	D
SOIL RESISTIVITY	3000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.1540
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1975		
ACTUAL FIRST LEAK			



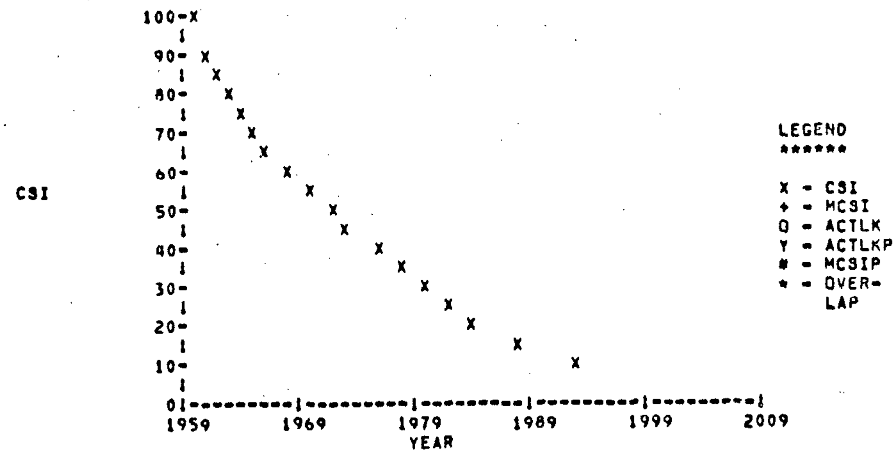
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	85	0	0
1962	79	0	0
1963	72	0	0
1964	67	0	0
1965	63	0	0
1966	59	0	0
1967	55	0	0
1968	51	0	0
1969	48	0	0
1970	45	0	0
1971	42	0	0
1972	38	0	0
1973	36	0	0
1974	33	0	0
1975	30	1	1
1976	26	2	3
1977	23	2	5
1978	20	3	8
1979	19	5	13
1980	17	7	20
1981	15	9	29
1982	13	12	41
1983	12	18	59
1984	10	24	83

Figure A12. CSI prediction report for Section D (wall thickness .1540).

CSI PREDICTION REPORT
REPORT DATE 06/21/83

PIPE ID	GAS J	SECTION NUMBER	F
SOIL RESISTIVITY	5000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.1540
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1980		
ACTUAL FIRST LEAK			



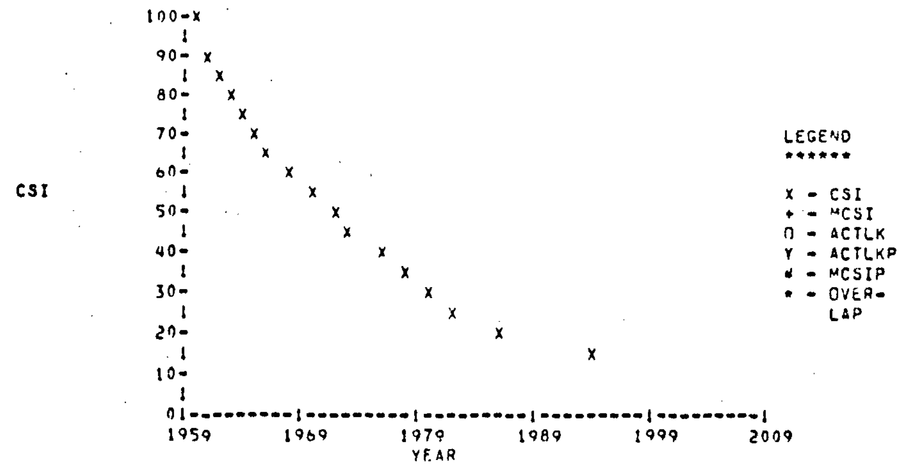
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	88	0	0
1962	82	0	0
1963	77	0	0
1964	72	0	0
1965	69	0	0
1966	65	0	0
1967	62	0	0
1968	59	0	0
1969	56	0	0
1970	53	0	0
1971	51	0	0
1972	48	0	0
1973	45	0	0
1974	43	0	0
1975	41	0	0
1976	38	0	0
1977	36	0	0
1978	34	0	0
1979	32	0	0
1980	30	1	1
1981	26	1	2
1982	25	2	4
1983	22	2	6
1984	20	3	9
1985	19	3	12
1986	17	4	16
1987	16	5	21
1988	15	6	27
1989	14	7	34
1990	13	9	43
1991	12	11	54
1992	11	13	67
1993	10	15	82

Figure A13. CSI prediction report for Section F (wall thickness .1540).

CSI PREDICTION REPORT
REPORT DATE 06/15/83

PIPE ID	GAS J	SECTION NUMBER	H
SOIL RESISTIVITY	7000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.1540
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1980		
ACTUAL FIRST LEAK			



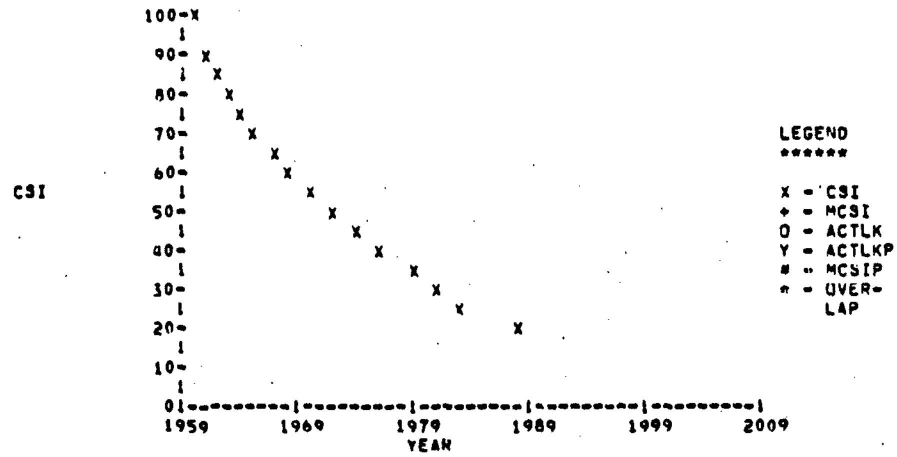
GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	88	0	0
1962	82	0	0
1963	77	0	0
1964	72	0	0
1965	69	0	0
1966	65	0	0
1967	62	0	0
1968	59	0	0
1969	56	0	0
1970	53	0	0
1971	51	0	0
1972	48	0	0
1973	45	0	0
1974	43	0	0
1975	41	0	0
1976	38	0	0
1977	36	0	0
1978	34	0	0
1979	32	0	0
1980	30	1	1
1981	26	1	2
1982	24	1	3
1983	23	1	4
1984	22	2	6
1985	21	1	7
1986	20	2	9
1987	19	2	11
1988	19	1	12
1989	18	2	14
1990	17	2	16
1991	17	2	18
1992	16	3	21
1993	16	2	23
1994	15	3	26
1995	15	2	28
1996	15	3	31
1997	14	3	34
1998	14	4	38
1999	13	3	41
2000	13	4	45

Figure A14. CSI prediction report for Section H (wall thickness .1540).

CSI PREDICTION REPORT
REPORT DATE 06/15/83

PIPE ID	GAS J	SECTION NUMBER	J
SOIL RESISTIVITY	9000.00	SOIL PH	7.00
COATING MATERIAL	COAL TAR	WALL THICKNESS	.1540
YEAR INSTALLED	1960		
PREDICTED FIRST LEAK	1981		
ACTUAL FIRST LEAK			



GRAPH TABLE

CSI YEAR	CALCULATED CSI	NUMBER OF LEAKS	TOTAL # LEAKS
1960	100	0	0
1961	88	0	0
1962	82	0	0
1963	77	0	0
1964	73	0	0
1965	70	0	0
1966	66	0	0
1967	63	0	0
1968	60	0	0
1969	57	0	0
1970	54	0	0
1971	52	0	0
1972	49	0	0
1973	47	0	0
1974	45	0	0
1975	42	0	0
1976	40	0	0
1977	38	0	0
1978	36	0	0
1979	34	0	0
1980	32	0	0
1981	30	1	1
1982	26	1	2
1983	25	1	3
1984	23	1	4
1985	23	1	5
1986	22	1	6
1987	21	1	7
1988	20	1	8
1989	20	1	9
1990	20	1	10
1991	19	1	11
1992	19	1	12
1993	18	1	13
1994	18	1	14
1995	18	1	15
1996	17	1	16
1997	17	1	17
1998	17	1	18
1999	17	1	19
2000	16	1	20
2001	16	1	21

Figure A15. CSI prediction report for Section J (wall thickness .1540).

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